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WDM Optical Network

Efficient Techniques for fault-tolerant logic topology design

By

QI Shen

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
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Abstract

The rapid increase of bandwidth intensive applications has created an unprecedented demand for bandwidth on the Internet. With recent advances in optical technologies, especially the development of wavelength division multiplexing (WDM) techniques, the amount of raw bandwidth available on the fibre links has increased by several orders of magnitude.

Due to the large volume of traffic these optical networks carry, there is one very important issue – design of robust networks that can survive faults. Two common mechanisms to protect against the network failure: one is protection and another is restoration.

My research focuses on studying the efficient techniques for fault-tolerant logical topology design for the WDM optical network. In my research, the goal is to determine a topology that accommodates the entire traffic flow and provides protection against any single fiber failure. I solve the problem by formulating the logical topology design problem as a MILP optimization problem, which generates the optimum logical topology and the optimum traffic routing scheme.

Keyword: WDM, Wavelength Routed Network, Lightpath, Physical Topology, Logical Topology, Single-hop, Multi-hop, Routing and Wavelength Assignment (RWA), Protection, Restoration, MILP.

Acknowledgement

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Thanks to the entire optical network group for their support and cooperation.

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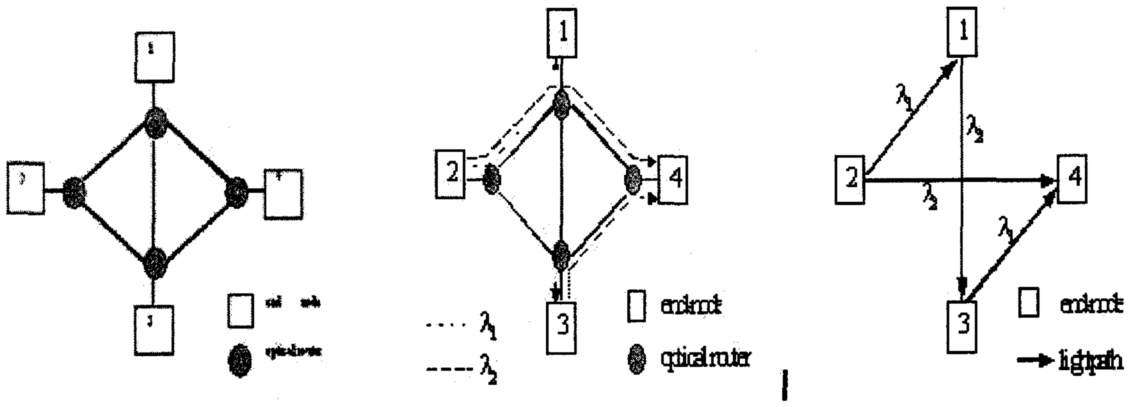
Chapter 1: Introduction

In our information-dependent society, the information is provided to us through a global mesh of communication networks [Muk97]. More and more users are starting to use networks and bandwidth-intensive networking applications, such as data browsing on the World Wide Web, java applications, video conference. Virtually all of these services are transported together on relatively few "backbone" fiber transmission systems. This creates an acute need for the very high-bandwidth transport network facilities, with capabilities much beyond those that the current high-speed networks (ATM) can provide. Over the last 20 years, optical fibers have evolved to become the most attractive transmission medium for high-speed communication, because of its capabilities of high bandwidth, low error rate and low loss. Optical Wavelength Division Multiplexing (WDM) is a technology that offers the potential to exploit the enormous bandwidth available in existing fiber to meet the increasing demand for bandwidth in the Internet today and in the future. Wavelength Division Multiplexing (WDM) divides the tremendous bandwidth available in a fiber into many non-overlapping wavelengths (or wavelength channels) and enables data transmission over these channels simultaneously. Each channel can operate at an electronic speed of a few gigabits per second. The number of channels in an optical fiber is determined by the technology used and a value up to 200 channels per fiber has been reported.

1.1 Physical and Logical Topology

Wavelength Routed (WR) optical networks, which employ Wavelength Division Multiplexing (WDM), are attractive candidates for the next generation of wide-area backbone networks. In WR Optical networks, the basic mechanism of communication is a *lightpath*, which is an all-optical communication channel between two nodes in the network. A single lightpath may span more than one fiber link. A connection request is carried by a lightpath from the source node to the destination node. Without wavelength converters, a lightpath would use the same wavelength on the all fibre links it traverses. This is called the wavelength-continuity constraint. To avoid inference between the signals, two lightpaths on the same fiber must use different wavelengths. Wavelength routing switches are used to optically route the signal for a given lightpath over multiple fibers from the source node to the destination node.



(a) Physical Topology (b) Physical topology with lightpath (c) Logical Topology

Figure 1.1 Wavelength-routed Optical Network

As shown in figure 1.1(a), the physical topology of a network consists of optical wavelength routers (routing nodes) interconnected by pairs of point-to-point fiber links to form an arbitrary physical topology [RS96]. Each fiber link consists of a pair of unidirectional fiber links with the capability of carrying a limit number of wavelengths. End nodes are connected to the wavelength router. Each end node is equipped with a set of transmitters and receivers, which are tuned to the wavelength on which a certain lightpath operates. End nodes are the nodes can only generate, send and receive data, but cannot route data. We can combine an end node with a wavelength router together as a network node.

Figure 1.1(b) shows a set of lightpaths supported by the physical topology. A logical topology can be embedded on a given physical fiber network by setting up a particular set of lightpaths between end nodes. In a logical topology, the vertices correspond to the network nodes of the physical topology, and the directed edges correspond to the lightpaths that have been set up on physical topology. For example, if there is a lightpath between the nodes **2** to **4**, in the physical topology, then there will be a direct edge from **2** to **4** in the logical topology. Figure 1.1(c) shows the logical topology corresponding to the set of lighpaths shown in figure 1.1(b). It is clear that a given physical topology can support many different logical topologies with different lightpath assignments.

The physical degree of a node is the number of physical links that directly connect that node to other nodes. For example, the physical degree of nodes 2 and 4 in figure 1.1(a) is 2 and of nodes 1 and 3 is 3. The logical out-degree of a node is the number of lightpaths that originate from that node and the logical in-degree of a node is the number of lightpaths that terminate at that node. For example (figure 1.1(c)), the logical out-degree of nodes 1 and 3 is 1, of node 2 is 2, and of node 4 is 0. The logical in-degree of nodes 1 and 3 is 1, of node 4 is 2, and of node 2 is 0 [MR96].

1.2 Motivation

In Wavelength Routed Optical Networks (WRONs), a logical topology is typically overlaid on a physical topology. An arbitrary logical topology may be defined using any given physical fiber network. In such overlay architecture, the logical topology makes the physical topology invisible to the higher layer networks.

For a given physical topology, it can support many different logical topologies with different lightpaths assignments. Our problem is to define which is the best logical topology. So the logical topology design problem is actually an optimization problem. The logical topology is typically obtained as a solution to a mixed integer linear programming (MILP) problem. The optimization criterion can vary such as, minimizing the average hop distance in the network, maximizing flow (congestion) in a lightpath, or minimizing the total number of lightpaths. In our study, we will concentrate on the minimization of the congestion of the network. congestion is defined as the maximum amount of traffic flow on any lightpath.

The most frequent cause for failure in WDM networks is a fiber cut due to a break in any fiber in the network. Because a single fiber supports multiple lightpaths, even a single fiber failure may lead to the large data losses. Therefore, handling the fiber failure is of prime importance in WR optical networks. There are two broad approaches to handling the failure in WDM networks, one is the protection and another is restoration. In protection, which is a static scheme, backup paths and wavelengths are reserved in advance at the time call setup. In restoration, which is a dynamic scheme, backup paths are discovered upon the occurrence of a failure. In this thesis, to protect against fiber failure, we use the protection approach where each primary path is allocated a backup path in advance.

Recently, a number of researchers have proposed strategies to design fault tolerant logical topology in WDM networks and some approaches formulate the problem as a Mixed Integer Linear Program (MILP). The solution of the MILP formulation provides an optimal logical topology and an optimal scheme for routing the traffic between every source-destination pair. For example, some principles for designing a WDM optical network with protection are addressed in [RM99][SRM02]. Routing and wavelength assignment approaches for wavelength-routed optical WDM networks are reviewed in [ZJM00]. However, These formulations are computationally infeasible for practical networks. For example, in [GU03], Hong Guan proposed a complete MILP formulation for determining the optimum logical topology, the optimal routing and wavelength assignment for the lightpaths corresponding to each logical edge and how the traffic should be routed over the logical topology. Using this formulation, it takes several days to get the solution even for a small four-nodes network.

In this thesis, we propose a new MILP formulation that can describe the problem more efficiently. This new MILP formulation reduces the complexity of the problem and the approach is computationally tractable for large networks.

Based on the motivations mentioned before, the main goals of this thesis are to:

1) Design the optimum logical topology based on available resource.
2) Make the designed logical topology fault tolerant.
3) Make the problem formulation as efficient as possible.

1.3 Problem Outline

In this thesis, our interest is to develop the efficient techniques for optimization of fault-tolerant logic topology design. The logical topology design problem, the issue of setting up lightpaths and routing the lightpaths over the physical fibers and switches of a given physical topology, is an optimization problem in which the overall network performance must be balanced against the consumption of network resources. Ideally, we would like to set up lightpaths between all the $N(N-1)$ node pairs for a N nodes network. However, this is usually not possible because the number of wavelengths available per fiber and the amount of hardware that can be provided (transmitters and receivers) is limited. A higher number of channels may provide more network capacity, but it also results in higher network costs, and in some cases, may require more complex protocols.

Once a set of lightpaths has been chosen or determined, we need to route each such lightpath in the network and assign a wavelength to it. This is referred to as the routing and wavelength assignment (RWA) problem. Formally, the RWA problem can be stated as follows. Given a set of lightpaths that need to be eatablished on the network, and given a constraint on the number of wavelengths, determine the wavelengths that should be assigned to these lightpaths so that the maximum number of lightpaths may be established [Mu97]. Logical topology design is actually a combined problem of selecting lightpaths and RWA.

There are two approaches used to solve the logical topology design problem. The first approach involves a Mixed Integer Linear Programming (MILP) formulation, which generates the optimum logical topology and the optimum traffic routing scheme. However solving this MILP formulation takes a very long time. Another approach is based on a heuristic algorithm, which creates a suboptimum logical topology. This approach can solve the problem very quickly, but it cannot provide any guarantees on the performance and suitability of the solution.

To develop efficient optimization techniques for fault-tolerant logic topology design, there are three components in the description of process.

- Determine the set of lightpaths that constitute the logical topology.
- Determine optimal routing and wavelength assignment for each selected lightpath corresponding to each logical edge.
- Determine how traffic should be routed over the logical edges.

Though we consider the problem as several components, these steps are not independent, but are very inter-related. For example, the lightpaths must be chosen such that there is a valid routing and they can accommodate all the traffic. But we cannot do the RWA unless the set of LP's are known. This makes problem very difficult.

1.4 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 will provide thesis related literature review of the basic terminology and techniques of WDM networks and fault management techniques for WDM networks and a brief introduction to MILP(Mixed Integer Linear Programming).

Chapter 3 includes an overview of our research, which solve the logic topology design problem with shared-path protect mechanism.

Chapter 4 provides the analysis of the MILP formulation proposed in our research that design the optimal logical topology and the routing and wavelength assignment problem (RWA).

Chapter 5 analyzes the results of experiments for some small to moderate networks.

Chapter 6 concludes the thesis with some critical summary and future work.

Chapter 2: Background Review

Due to the growth of the services available online and the number of the connected users, the Internet and the World Wide Web today are facing a constant increase in bandwidth demand in network Optical networking is one key technology to fulfill the demands for bandwidth.

To exploit the fiber's huge bandwidth, concurrency among multiple user transmission is introduced into the network architectures and protocols. In an optical communication network, this concurrency may be provided according to either wavelength or frequency, which includes wavelength-division multiplexing (WDM), time-division multiplexing (TDM), or code-division multiplexing (CDM). Specifically, WDM is current favorite multiplexing technology for optical communication networks since all of the end-user equipment needs to operate only at the bit rate of a WDM channel, which can be chosen arbitrarily, e.g., peak electronic processing speed. [Muk97].

In this chapter, we will give thesis related literature review of the basic terminology and techniques of WDM networks, fault management techniques for WDM networks and a brief introduction to MILP (Mixed Integer Linear Programming).

2.1 WDM Network

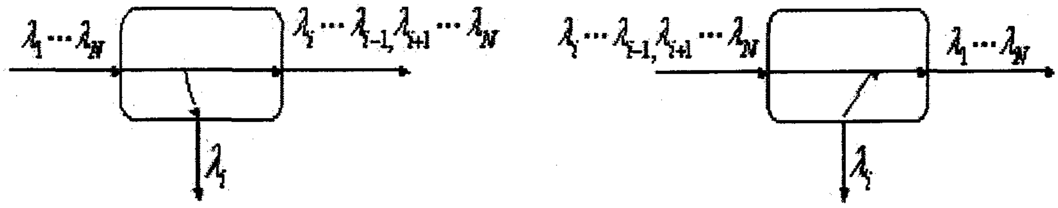
Driven by the increasing demands for high bandwidth, WDM technology is being deployed by several telecommunication companies for point-to-point communications. In WDM, the vast transmission bandwidth available on a fiber is divided into several different smaller capacity channels and each of these channels can be operated at moderate bit rate (2.5-10 Gb/s) [AQ02]. Each channel corresponds to a different wavelength and many users can use these different channels simultaneously. This way, the aggregate network capacity can reach the number of channels times the rate of each channel. A fuller discussion of wide area optical networks can be found in [Muk97] [RS98] [Qi00][SRM02].

2.1.1 Network Components

Optical fiber: The optical fiber has evolved to become the most attractive transmission medium for high-speed communication, because of its potentially limitless capabilities of high bandwidth, low error rate and low loss.

Figure 2.1 Optical Fiber

Wavelength add-drop multiplexers (WADM) will selectively add or drop a specific wavelength on a WDM fiber [Muk97]. Traffic on certain wavelengths can be passed through the WADM without opto-electronic conversion, while traffic on other wavelengths is terminated optically (dropped) and traffic on new wavelengths can be added into the WDM fiber. As shown in figure 2.2(a), the traffic on wavelength channel λ_i is dropped while it passes through WADM. The new traffic can be added into the WDM fiber through this wavelength channel (λ_i) as shown in figure 2.2(b). The traffic on other wavelength channels ($\lambda_1 \cdots \lambda_{i-1}, \lambda_{i+1} \cdots \lambda_N$) are optically passed through.



(a) drop function in WADM

(b) add function in WADM

Figure 2.2 Wavelength add-drop multiplexer

The Wavelength Router (WR) is a more powerful system than a WADM. It provides the ability to route or switch individual optical signal (at each of the wavelength) on any of its input port to any output port without undergoing the opto-electonic conversion. A WR with N inputs and N outputs capable of handling W wavelengths can be thought of as W independent N×N switches. These switches have to be processed by a wavelength demultiplexer and followed by a wavelength multiplexer to implement a WR as shown in figure 2.3 [DR00]. An all-optical communication channel (lightpath) can be established between two end-nodes by employing the WRs at intermediate nodes [GU03]. Equipped with a wavelength converter, a WR can optically switch an incoming signal from any of input port at a wavelength to any output port on a different wavelength. Both WADM and WR provide the flexible connection between the end-nodes.

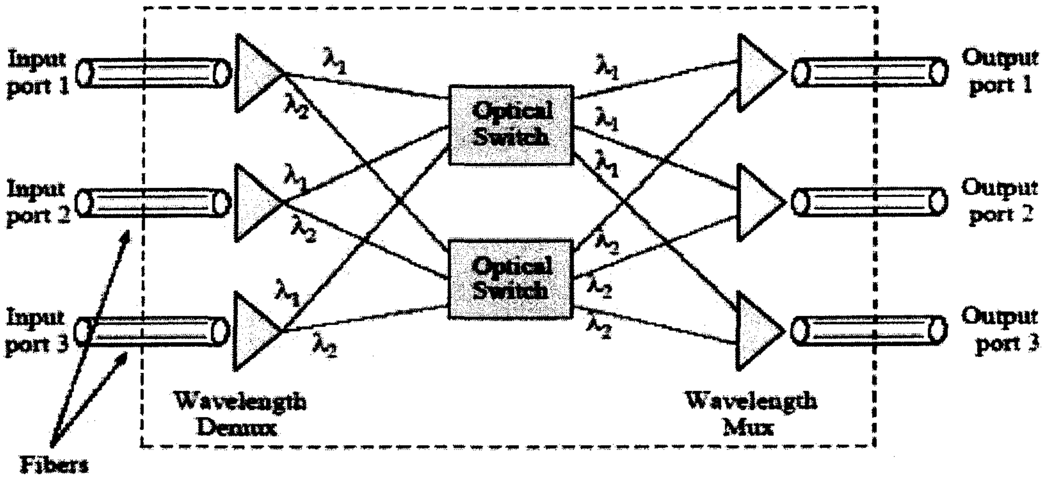


Figure 2.3 A Wavelength Router [DR00]

In order to develop an effective WDM network, the tunable transmitter/tunable receiver and/or a multitude of fixed transmitters/receivers are employed at end nodes to enable each user to transmit into and receive from multiple channels.

There are two important technologies that have been developed in order to enable the transfer of data over WDM: broadcast-and-select and wavelength-routed. In this thesis, we will concentrate on the wavelength-routed network.

2.2 Wavelength-routed Network

A wavelength-routed network, which employs wavelength-division multiplexing and wavelength routing, offers an enormous potential for future high-capa$\lambda_i$city wide-area network [Al93] [Br93]. A WR optical network is capable of selectively routing and switching individual wavelengths. The intelligent optical components, such as Wavelength Router (WR), wavelength add-drop multiplexers (WADM), etc, are used to enable the deployment of WR optical networks. A wavelength-routed optical WDM network is shown in Fig.2.3.

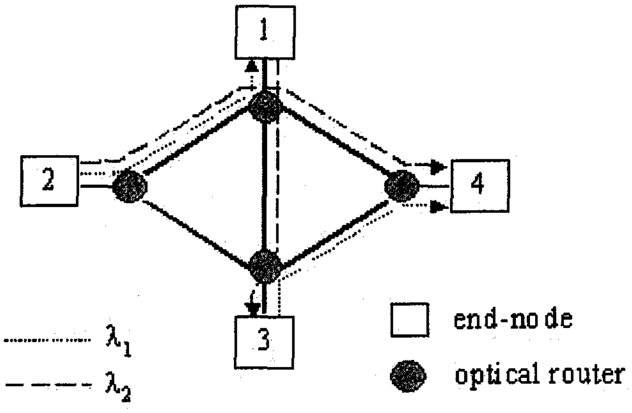


Figure 2.4 Wavelength-routed Network (Physical Topology)

The basic mechanism of communication in a WR optical network is a lightpath, which is a clear all-optical communication channel between two nodes in the network, and it may span several fiber links [Muk97]. A connection request can be implemented by a lightpath from source node to the destionation node without optoelectronic conversion at the intermediate nodes. For example, in Fig2.4, lightpaths are established between nodes **2** and **4** on wavelength channel λ_2, between **2** and **1** on wavelength channel λ_1, and between **1** and 3 on wavelength channel λ_2, between **3** and 4 on wavelength channel λ_1.

The requirement known as the wavelength continuity constraint is that a lightpath should be on the same wavelength channel throughout its path, which indicates that a lightpath consists of a single wavelength over a sequence of physical links [DR00]. This requirement may not be necessary if we employ wavelength converters in the intermediate nodes. However, due to the high cost of wavelength converters, most proposed optical networks do not allow wavelength conversion. In this thesis, we assume the wavelength continuity constraint. Another fundamental requirement known as distinct wavelength constraint is that two or more lightpaths traversing the same fiber link must be on different wavelength channels so that they do not interfere with one another.

WR optical network has an inherent property of transparency, which means that the lighpaths can carry data at a variety of bite rates, and protocol [RS98]. This enables the optical layer to support a variety of higher layers concurrently. For example, the wavelength λ_1 can carry SONET data, whereas λ_2 can carry ATM cells or other traffic.

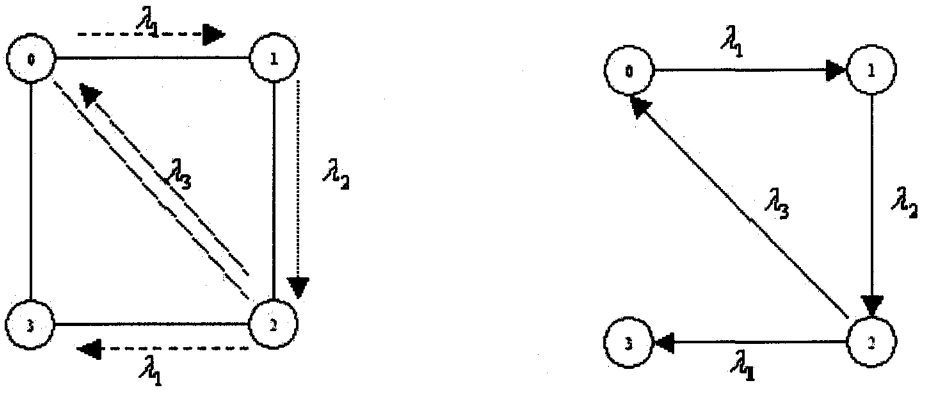
Another important property of WR optical network is wavelength reuse, which means that two lightpaths can be assigned the same wavelength as long as they do not share the same fiber. Thus the network can support much larger number of lightpaths than the number of available wavelength and provide the network with enormous capability. For example the lightpaths $2 \rightarrow 4$, $1 \rightarrow 3$ are assigned the same wavelength λ_2.

2.3 Single-hop and multi-hop networks

The logical topology is a combination of the well-known "single-hop" [Muk92a] and "multihop" [Ac87] [CGK92] [Muk92b] approaches. A hop is defined as a logical connection between two nodes without any opto-electronic processing at intermediate devices.

A single-hop WR optical network, which only uses the optical switching component at the intermediate nodes, allows communication between any source-destination pair using a single lightpath without any opto-electronic conversion in the intermediate node.

Because of limitations on the number of wavelengths that can be used and hardware constraints at the network nodes, it is not possible to set up a lightpath between every pair of end nodes [DR00]. For example, a N nodes netowrk needs to set up N(N-1) lighpaths between all pair of end nodes. When it is not possible to establish lightpaths between all pairs of nodes, an alternative approach is needed. In multi-hop networks [Muk92b], packets from a source node to a destination node might hop through some intermediate nodes. At these intermediate nodes, the packet coming in on a ligthpath must be converted from optical form to electronic form, switched electronically and then converted back to optical form and sent out on a different lightpath to their destination.



physical topology logical topology

Figure2.5 Physical topology and logical topology

In figure 2.5, we can see node **0** can reach node **1** in one hop on wavelength λ_1, and node **1** can reach node **2** in one hop on wavelength λ_2. Because there is no direct lightpath between the node **0** and node **2**, we need to use the multihop approach when a communication request coming from the node **0** is destined for node **2**. The packets sent from the node **0** will arrive at the node **1** on wavelength λ_1. The signal will undergo the opto-electronic conversion at node **1** and will be sent to node **2** on a different wavelength λ_2.

In optical networks, communication using a single lightpath is relatively fast. Because the process of buffering at intermediate nodes using electronic media adds additional delay in the communication, communication using a sequence of lightpaths limits the speed at which traffic can be sent from the source to the destination node. In our thesis, we assume the multi-hop networks.

2.4 Logical Topology design and Routing Problem

As mentioned before, the logical topology design problem, the issue of setting up lightpaths and routing the lightpaths over the physical fibers and switches, is an optimization problem in which the overall network performance must be balanced against the consumption of network resources. With different lightpath assignments, the same physical topology can have many different logical topologies. The selection of the best logical topology and of the associated routing strategy depends on the traffic pattern that must be transported by the network. Recent research of how to design a logical topology over a wavelength-routed physical topology can be found in [LMM00] [DR00] [GL01].

2.4.1 Logical Topology Design

The problem of designing a desired logical topology over a physical topology is formally stated below [MRBM94].

The input of the problem:

1) An existing physical topology $G_p = (V, E_p)$, where V is the set of networks nodes and E_p is the set of fiber links connecting the nodes. Each link in the physical topology is bi-directional.
2) The limited number of wavelength channels carried by each fiber.
3) The limited number of wavelength-tunable transmitters and wavelength-tunable receivers at each node
4) A description of N × N traffic pattern T exchanged by source and destination nodes, where N is the number of network nodes.

Our goal is to determine the following:

1) A logical topology $G_v = (V, E_v)$, where V is the nodes of the logical topology (which correspond to the nodes in the physical topology) and E_v is set of direct all-optical lightpaths between node pairs.
2) A physical route and wavelength assignment for each lightpath.
3) The traffic routing over the logical topology.

Communication between any two nodes now takes place by following a path (a sequence of lightpaths) from the source to the destination node on the logical topology.

2.4.2 Routing and Wavelength Assignment (RWA)

The problem of designing logical topology is strongly associated with the routing problem [MET99]. In logical topology design, firstly we need to select and determine a set of lightpaths in terms of their source and destination nodes. This is constrained by the number of transmitters and receivers at the each node and a given traffic pattern. After a set of lightpaths has been chosen or determined, we need to route each such lightpath in the network and assign a wavelength to it. This is referred to as the routing and wavelength assignment (RWA) problem [Muk97]. Because these two steps depend on each other, normally we solve them together.

In the WR optical network, the routing and wavelength assignment are subject to the following two constraints: Wavelength continuity constraint and distinct wavelength constraint. So the objective of an RWA algorithm is to achieve the best possible performance within the limits of physical constraints.

The RWA problem can be classified into two broad versions: static RWA and dynamic RWA. In static RWA problem, the traffic patterns in the network are reasonably well-known in advance and any traffic variations take place over long time scales [Ro00]. This is the case for large transport networks or Wide Area Networks (WANs), in which the traffic demand is more fixed over time. In a dynamic RWA, edge nodes submit to the network requests for lightpaths to be set up as needed [Ro00]. Thus, connection requests are initiated in some random fashion. This is the case for data networks or Local Area Networks (LANs), in which the traffic demand frequently changes over time.

2.5 Survivability and Fault Management

As WDM networks carry large amount of data, a single link failure in the network may result in enormous data losses. So a highly available network, which is very resilient to network failure, is a very important requirement for WDM network. The research on examining the survivability of WDM networks can be found in [RM99][EHS00] [VCDJ00][Ra02] [La02].

2.5.1 Fault Management

The term Survivability refers to a network's ability to continue to provide services in the presence of failure. This can be achieved by providing protection and restoration in the network [RS98]. Protection is a predetermined failure recovery mechanism, in which a dedicated backup path and wavelength is reserved for every primary path in the network before a failure. Restoration is a dynamic failure recovery mechanism, in which the backup paths are set up dynamically only after the event of a failure [RM99a].

Two techniques, protection at the WDM layer and restoration at IP layer, have emerged as the leading contender for fault management in optical Networks [SRM02]. At the WDM layer (optical layer), we provide the protection schemes, in which a backup lighpath is setup for every primary path at the beginning of the call setup. At the IP layer, we provide the restoration schemes, in which the network will work properly after a fiber failure by using spare capacity in the network. Generally, restoration schemes are more efficient in utilizing capacity due to the sharing of the spare capacity, while protection schemes have a faster recovery time and provide guarantees on the recovery.

The most prevalent form of communication failure is the accidental disruption of buried telecommunication cables – fiber cut. A fiber cut causes a link failure. In almost all cases, protection mechanisms are designed to protect against a single failure. In our research, we focus on the protection technologies against single link failure in WDM layer.

2.5.2 WDM protection

The physical layer is close to most of the common failures on the network, such as a fiber cut. Survivability mechanisms in the optical layer involve detecting this and performing a simple switch to divert the traffic through an alternate path. This is called protection [EL96]. There are two approaches in WDM protection to protect against link failures: link protection and path protection.

In link protection approach, backup paths and wavelength are reserved around each link of the primary path during the call setup [RM99a].

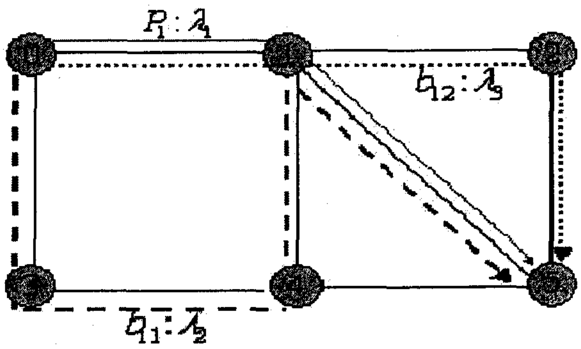


Figure 2.6 Link Protection

The link protection approach is shown in figure 2.6. It shows a one primary path p_1 and two backup path b_{11} and b_{12}. When the link $0 \rightarrow 1$ in primary path p_1 failed, we can use the backup path b_{11} to recovery it, when the link $1 \rightarrow 5$ in primary path p_1 failed, we can use the backup path b_{12} to recovery it.

In path protection, the backup path and wavelength are statically reserved on an end-to-end basis during call setup.

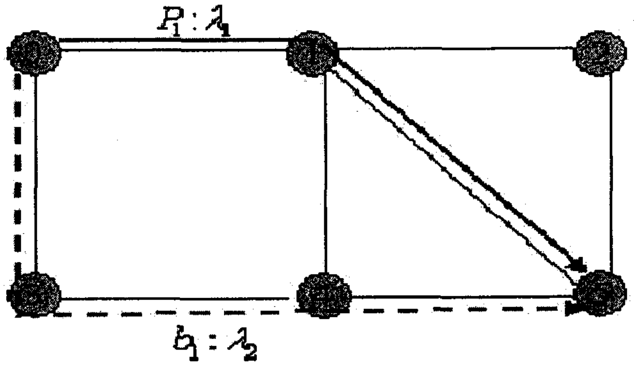


Figure 2.7 Path Protection

The path protection approach is shown in figure 2.7. It shows a primary path p_1 and its backup path b_1. When any link in the primary path p_1 failed, we can use the backup path b_1 to recovery it. In the link protection approach, for each link failure in a same primary path, we have to reserve an individual backup path for it. The path protection, which only reserves one backup path for a primary path, has the better resource utilization [MM03]. We use the path protection in our research.

In WDM path protection, the primary path and the corresponding backup path should be link (fiber)-disjoint. Otherwise, if the common fiber fails, the primary path and the backup path will both fail. There are two approaches in WDM path protection, one is dedicated-path protection; another is shared-path protection (also called backup multiplexing).

Dedicated-path protection

In dedicated-path protection, which is also called 1+1 protection, we reserve a link-disjoint backup path and wavelength, which is set up for each primary path at the beginning of the call connection. This wavelength, reserved on the links of the backup path, is also dedicated to the call and is not shared with other backup paths [RM99a].

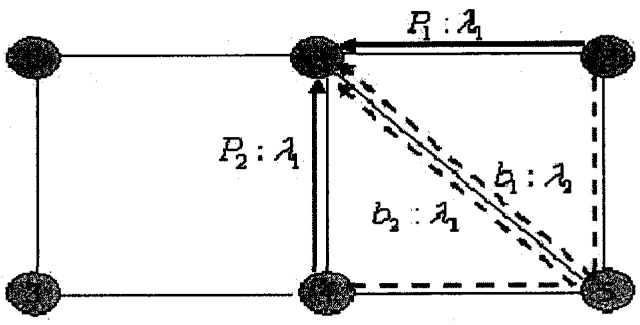


Figure 2.8 dedicated-path protection

An example of dedicated-path protection is shown in figure 2.8. The figure shows two primary paths p_1 and p_2 and their respective backup paths b_1 and b_2. The backup paths b_1 and b_2 are dedicated reserved for the primary path p_1 and p_2.

Shared-path protection

In shared-path protection, we also reserve a link-disjoint backup path and wavelength for each primary path. However, the wavelength reserved on the links of the backup path may be shared with other backup paths. If two primary paths are fiber-disjoint, then, under the single fiber fault assumption, they will never need to use their backup paths at the same time. Thus, their backup paths can share one or more fibers and be assigned the same wavelength on those fibers.

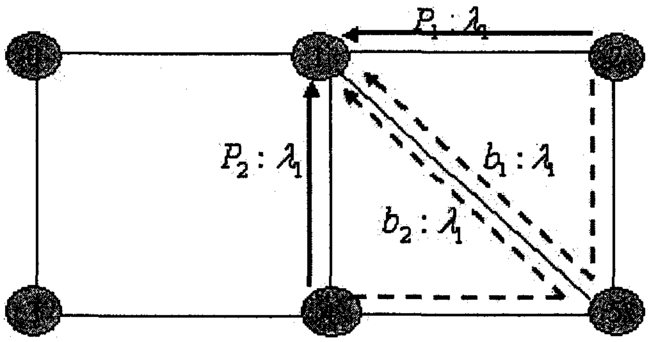


Figure 2.9 shared-path protection

The shared-path protection scheme is illustrated in figure 2.9. It shows two primary path p_1 and p_2, and their corresponding backup path b_1 and b_2. Since the primary path p_1 and p_2 are link-disjoint, their corresponding backup path b_1 and b_2 can share the same wavelength λ_1 on the same link $5 \rightarrow 1$. This shared link will be used by b_1 when primary path p_1 fails and by b_2 when primary path p_2 fails.

Shared-path protection has better capacity utilization than the dedicated-path protection, since backup channels are multiplexed among different failure scenarios, which are not expected to occur simultaneously [MM03]. In our research, we implement backup multiplexing.

2.6 Mixed Integer Linear Programming (MILP)

As mentioned before, the optimal logical topology is typically obtained as a solution to a mixed integer linear programming (MILP) problem. In this section, a brief introduction about MILP will be given.

MILP is used to solve the optimization problem, which is a computational problem in which the object is to find the best of all possible solutions. More formally, find a solution in the set of all possible solutions, which has the minimum (or maximum) value of the objective function. Optimization problem can be defined by three basic components [GU03]:

- An objective function – which determines how good a solution is.

- A set of variables – which affect the value of the objective function
- A set of constraints – which allow the variables to take on certain values but exclude others.

A linear programming (LP) problem is one in which the objective and all of the constraints are linear functions of the decision variables. Here is an example below:

$$\text{Maximize} \quad \sum_{j=1}^{n} c_j x_j$$

$$\text{Subject to} \quad \sum_{j=1}^{n} \partial_{ij} x_j \leq b_i \qquad i = 1, \ldots, m$$

$$\text{Variable} \quad x_j \leq 1$$

A mixed-integer linear programming (MILP) problem is a linear programming where some of the decision variables are constrained to have only integer values (i.e. whole numbers such as -1, 0, 1, 2, etc.) in the optimal solution. The use of integer variables greatly expands the scope of useful optimization problems that you can be define and solve. ILOG CPLEX is a tool for solving linear optimization problem, commonly referred to as Linear Programming (LP) problems.

Chapter 3: Overview of Our Work

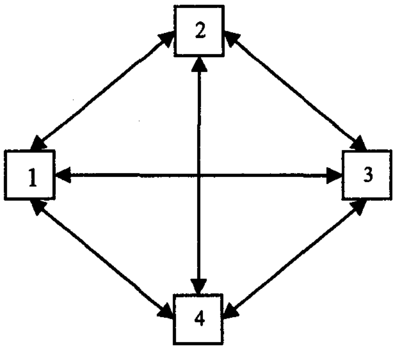
In this chapter, we present an overview of our research work. In our research, we need to define the WDM network model, which includes the physical topology, the fiber characteristics, the number of transmitters and receivers used at the end nodes, and the traffic matrix. Based on this network model, we explain the objectives of our research and the approach used to solve the problem. This approach proposes a Mixed Integer Linear Programming (MILP) formulation, which generates the optimum logical topology and the optimum traffic routing scheme.

3.1 Network Model

The physical topology consist of:

- N end nodes equipped with a limited number of tunable of transmitters and receivers.
- A number of wavelength routers used to route and switch the signal.
- The optical fibers connecting the network nodes support limited number of wavelengths.

Each WDM link between nodes i and j is bidirectional and consists of two unidirectional fibers. Each fiber can simultaneously carry the same set of wavelengths, λ_1, λ_2, …, λ_K, called the WDM channels. The capacity of each WDM channel (i.e. the maximum amount of traffic it can carry) is the same. In our model, the i^{th} end node has T_i^m transmitters and R_i^m receivers that are tuned to wavelength λ_m, $1 \leq m \leq K$. A typical network is shown in Figure 3.1a. Therefore, the total number of transmitters (receivers) at the i^{th} node is $\sum_{m=1}^{K} T_i^m$ $(\sum_{m=1}^{K} R_i^m)$.



(a) Physical network

$$T = \begin{bmatrix} 0.00 & 0.05 & 0.03 & 0.07 \\ 0.08 & 0.00 & 0.05 & 0.09 \\ 0.07 & 0.02 & 0.00 & 0.06 \\ 0.09 & 0.07 & 0.04 & 0.00 \end{bmatrix}$$

(b) Traffic Matrix

Figure 3.1. Network Model and traffic matrix

The description of the traffic flow is given by a $N \times N$ traffic matrix T, where N is the number of network nodes. Each entry of the matrix t_{ij} is the average rate of traffic from node i to node j. The traffic flows may be asymmetric, for example, the traffic flow from node to node j may be different from the traffic flow from node j to node i. Under a static traffic pattern, the connection requests are relatively stable and known in advance. Figure 3.1(b) shows an example of a traffic matrix for the network of figure 3.1(a). Each entry is expressed as a faction of the capacity of a lightpath. For example, the traffic from the node 1 to 2 is given as 0.05 in traffic matrix. If a lightpath in the network can carry

2.5 Gb/sec, then the actually traffic carried from node 1 to 2 is 1.25 Gb/sec. This entry t_{ij} represents the long-term average traffic between the node pair (i and j).

3.2 Objective

In our research, the objective is to minimize the congestion of the network, defined as the maximum traffic flow on any lightpath, which based on the physical topology and the traffic matrix T. The goal of this study is to determine the lightpaths, and hence define the logical topology to handle all the traffic requirements as specified by the traffic matrix T in most efficient way. For example, if a lightpath exists from node i to node j, the load offered to that lightpath is denoted by λ_{ij}. The component of this load due to traffic from source node s to destination node d on this lightpath is denoted by λ_{ij}^{sd}. The maximum of the logical loads is called congestion, and denoted by $F_{\max} = \max_{ij} \lambda_{ij}$.

The end-nodes have to convert the optical signal to electronic signal and vice-versa and a network with a lower of congestion means less conversion at the end-nodes [GH03]. The aim of creating the logical topology is to ensure that more traffic can be carried with fewer opto-electronic conversions along the way. Ideally, if we would like to set up lightpaths between all the $N(N-1)$ node pairs for a N nodes network. There is no opto-electronic conversion within the network except at the end nodes and we can get a network having a minimum value of congestion. However, the number of wavelengths available is usually too limited to allow this. So, in order to best exploit the capacity of the WDM network infrastructure, a crucial task is the identification of the best feasible logical topology. For a given physical network, the best logical topology is determined by the pattern of traffic flows over the network. In our research, the design method focus on minimizing the congestion level, based on the pattern of traffic flow over the network.

The value of the congestion of a network determines the factor by which the traffic matrix can grow and still be accommodated by the given logical topology. Therefore, minimizing congestion is desirable because it allows the maximum possible growth in the traffic matrix. For example if the congestion of a network is 0.5, then every entry in the traffic matrix can be doubled and the network would still be able to accommodate the entire traffic without allocation of any additional resources.

3.3 MILP Formulation

In our research, we use the MILP formulation to solve the WDM network optimization problem, and did the optimum for logical topology and traffic flow allocation. The objective function of the formulation is to minimize the network congestion F_{max}, which is the maximum amount of traffic flow on any lightpath.

In our research, our goal is to:

- Determine which lightpaths should be chosen. The set of potential lightpaths consists of all lightpaths between all $N(N-1)$ node pairs.
- Determine a primary path and a backup path for each chosen lightpath among three predefined routes, and assign the wavelength to each primary and back path.

- Determine how the traffic between each node pair will be routed from the source to the destination over the logical topology.

The constraints of the formulation are:

constraint 1) For a given source-destination pair, the corresponding primary path and the backup path must be fiber-disjoint. When a connection request arrives, we use the primary path to transfer the data. If the primary path fails, the backup path will be used to transfer the data. So to avoid the primary path and the backup path failing simultaneously, the primary path and the corresponding backup must use the different fibers on their routes.

constraint 2) Each primary path is edge-channel disjoint with every other primary path and backup path. According to the wavelength distinct constraint, on the same fiber, Two distinct lightpaths cannot use the same wavelength on the same fiber. Therefore, all lightpaths sharing a common fiber should be assigned different carrier wavelengths. So, if two primary paths share a common fiber through their routes, they cannot be assigned the same wavelength. Similarly, if a primary path and backup path use the same fiber, they also cannot be assigned the same wavelength.

constraint 3) Two backup paths can share the same channel on a fiber, if their corresponding primary paths are fiber-disjoint. In this thesis, we only consider the single fiber failure situation. When two primary paths use the different fibers through their route to transfer data, they can never fail at the same time. So, their corresponding backup paths will never be used at the same time. Hence we can assign their corresponding backup paths the same channel and route them through the same fibers.

constraint 4) Under fault free condition, the number of primary paths that use wavelength λ_m and originate from (terminating at) node u, should be less than the given number of transmitters (receivers) at node u, which are tuned to λ_m. This ensures that we have the requisite number of transmitters (receivers) at each node.

constraint 5) Suppose a fiber fails and this destroys several primary paths, the total number of lightpaths, including the working primary paths and the backup paths that replace the unusable primary paths, originating from (terminating at) node u and using wavelength λ_m cannot exceed the number of transmitters (receivers) at node u tuned to λ_m,

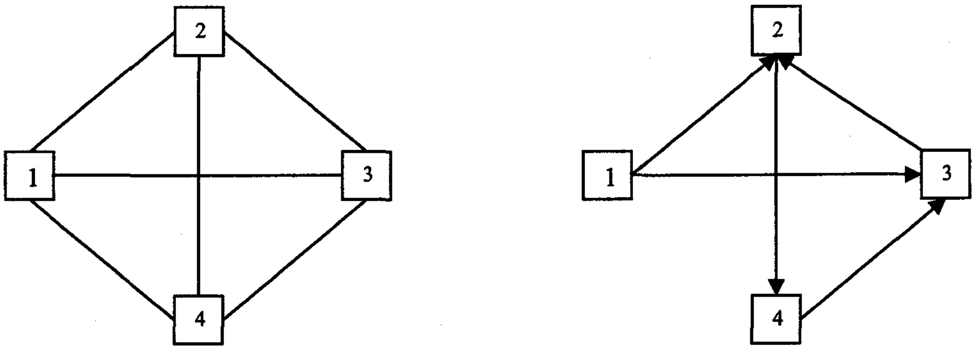
constraint 6) The amount of traffic t_{ij} from i to j may be handled using a number of routes. If more than one route is used to handle t_{ij}, then each route carries only a part of t_{ij}, and the sum of the traffic carried by these routes is $t_{ij..}$ The maximum amount of traffic flow on any lightpath is $F_{max.}$ The maximum capacity of a lightpath is 1. The total amount of traffic flow on any lightpath is less than 1.

We use CPLEX 7.5 [IL01], a powerful optimization tool, to solve this MILP formulation. The solution of this problem provides us the optimal logical topology and gives us a routing scheme over the logical topology.

3.4 Simple Example

This section we will give a simple example to explain how the problem solved. Based on the network model given above, our MILP formulation includes the following steps:

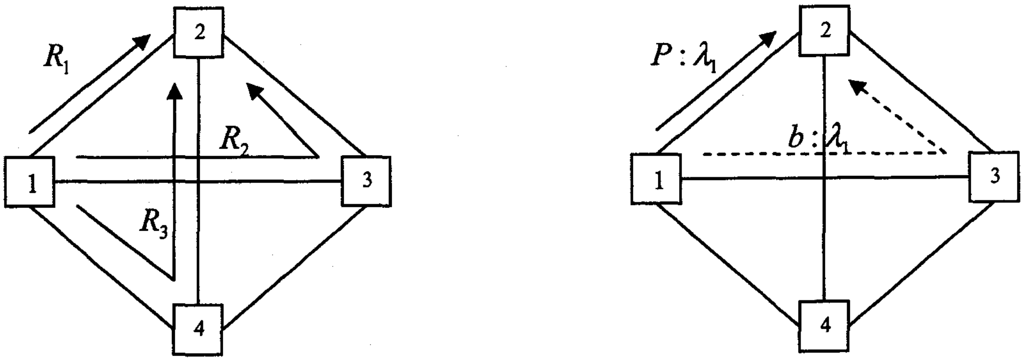
Step 1: Select a set of lighpaths between the nodes, constrained by the number of transmitters and receivers at each end node and a given traffic pattern. As shown in figure 4.1(b), the following set of lightpaths $1 \rightarrow 2$, $1 \rightarrow 3$, $3 \rightarrow 2$ and $4 \rightarrow 3$ has been chosen.



(a) Physical topology (b) logical topology

Figure 4.1 The example of step 1

Step 2: We determine the optimal routing and wavelength assignment for the lightpaths corresponding to each logic edge. Since we use WDM path protection scheme, for each communication request, we need to find a primary and backup route and assign the wavelength available to both. To decrease the number of integer variables in the MILP formulation, we find a primary and backup route among three pre-determined routes. In our formulation, we use the Dijkstra's algorithm, which is a algorithm to find the shortest path in the network, to find three shortest routes for each s - d node pair. For the lightpath from the node 1 to node 2, we need to route the primary route and backup route. From the 3 shortest routes for node pair 1-2 ($1 \rightarrow 2$, $1 \rightarrow 3 \rightarrow 2$, $1 \rightarrow 4 \rightarrow 2$), we select one route for primary path and another for backup path (figure 4.2 (b)). We assign the wavelength λ_1 for primary path, and the wavelength λ_1 for the backup path.



(a) Physical topology (b) Physical topology

Figure 4.2 The example of step 2

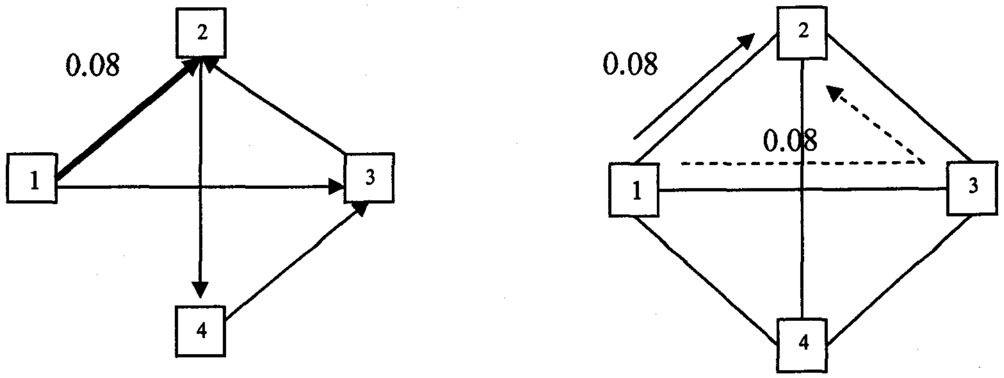
Step 3: We route the traffic over the logical topology. Each traffic request between a source-destination pair can be accommodated by one or more lightpaths. For the set of e lightpaths over logical topology, the traffic request between the source-destination pair (1, 2) can be carried

i) Entirely through the lightpath 1-2 (single hop).

ii) Entirely through the lightpaths 1-3, 3-2 (multi-hop).

iii) Partly the traffic on lightpath 1-2 and partly the traffic on lightpaths 1-3, 3-2.

In our example, we just consider the case one, that all the traffic request between source-destination pair (1, 2) is carried through the lightpath 1-2, as shown in Figure 4.3.



(a) Logical topology (b) Physical topology

Figure 4.3 The Example of step 3

Even though we divide this problem into three steps, however, these steps are not independent, but are very inter-related. These three steps will be solved together by using the MILP formulation, which makes out formulation very complex and takes a relatively long time to solve.

Chapter 4 Logical Topology Design

In this chapter, we describe our MILP formulation in detail. We are given a physical topology of a WDM optical network G = (N, E), where N is the set of networks nodes and E is the set of fiber links connecting the nodes. Each link in the physical topology is bi-directional. Each fiber carries a limited number of wavelength channels, and each node is equipped with a limited number of transmitters and receivers. We are also given a description of the traffic pattern expressed as a $N \times N$ matrix T, exchanged by source and destination nodes, and a set of potential lightpaths consists of all lightpaths between the $N(N\text{-}1)$ node pairs.

Given the information above, we can solve our MILP formulation to obtain

1) A set of lightpaths selected to constitute the logical topology
2) The primary and backup path routing (among three predefined routes) for each selected lightpath, and wavelengths assignment for each lightpath.
3) The traffic flow on each selected lightpath.

The main complexity of the MILP formulation is the number of the integer variables used in the formulation. This makes the problem very complicated and takes a very long time to solve the MILP problem. To simplify our MILP formulation, we need to reduce the number of the integer variables used in the formulation. In our study, we chose one of three edge-disjoint alternative paths between each source-destination pair for the primary or backup path. This will reduce the number of the integer variables used and simplify our MILP formulation.

4.1 Create Shortest Paths

Before we begin to do our MILP formulation, we need to find three edge-disjoint shortest paths for every node pair in the network. When we want to establish a lightpath between a particular source-destination pair, we choose one of these three paths as the route for the primary path and another as the route for the backup path. Since the primary route and the backup route must be edge-disjoint, it is convenient to consider only edge-disjoint paths. We accomplish this by successively applying Dijkstra's algorithm [Ski97] to each node pair. When attempting to find a new shortest path for a given node pair, we erase the edges used by the previously found shortest paths for this node pair and use the modified graph to create the next shortest path. This ensures that all three shortest paths will be edge-disjoint [HM03].

4.2 The MILP Formulation

MILP formulation is used to solve the optimization problem, which is a computational problem in which the object is to find the best of all possible solutions. A MILP formulation includes three components: an Objective function, a set of variables, and a set of constraints. In this section, we will introduce MILP formulation proposed in our research.

4.2.1 Notation

In this section, we define the notation employed to formulate the MILP. We are given the following: (a) the network topology represented as a directed graph G = (N, E), (b) a demand matrix T, and (c) alternate routing tables at each nodes. Also given are the following:

- N: Nodes in the network, numbered 1 through N, $|N| = n$.
- Node-pair are numbered 1 through $N \times (N-1)$.
- E: Edges in the network, numbered 1 through E, $|E| = m$.
- K: Maximum number of wavelength on a link, $|K| = k$.
- P: The set of potential lightpaths, $|P| = p$.
- R: The set of alternate routes for each node pair. In our study, the maximum number of alternate routes between any node-pair is 3, $|R| = 3$.
- O(p): the source node of lightpath p.
- L(p): the destination node of lightpath p.
- $\Lambda = (\lambda^{sd})$ is a $n \times n$ static traffic matrix, where λ^{sd} representthe average traffic exchanged between a source s and destination d.

4.2.2 Constants

In this section, we define a constant that used in our formulation. The description of this constant is given below.

$d_e^{pr} = 1$, if route r of lightpath p uses edge e.

This constant can used to reduce the number of integer variables in our formulation. For each lightpath p^{th}, it will be routed through one or more edges in the physical topology.

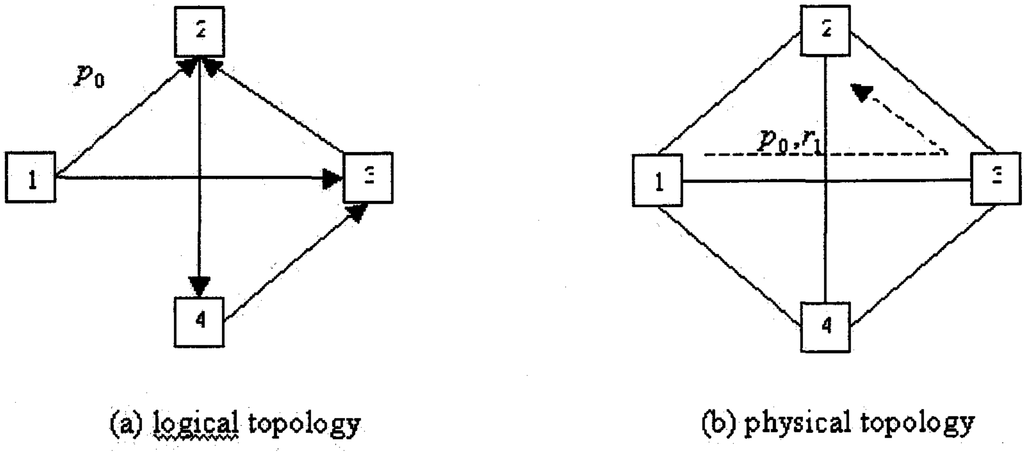

(a) logical topology (b) physical topology

Figure 4.1 The example for constant d_e^{pr}

From the figure 4.1, we can see, for the lightpath (p_0) in the logical topology, we need to find a route (r_1) in the physical topology for it. The route r_1 of lightpath p_0 uses two edges $1 \rightarrow 3$ ($e = 2$) and $3 \rightarrow 2$ ($e = 7$). So, the variables $d_e^{pr} = 1$, if the $e = 2$ or $e = 7$ for the route r_1 of lightpath p_0. The variables $d_e^{pr} = 0$ for the other value of e for the route r_1 of lightpath p_0. In our formulation, we only consider when the variables d_e^{pr} = 1, this means we only consider when e takes value 2 and 7. This will reduce the number of the integer variables used in the formulation.

4.2.2 Binary Variables

In this section, we define the binary (0-1 integer) variables that used in our formulation. The description of these variables is given below:

Lightpath selection binary variables b_p

$$b_p = \begin{cases} 1, \text{if lightpath p is selected.} \\ 0, \text{otherwise} \end{cases}$$

The binary variable b_p is used to select a set of lightpaths that constitute the logical topology. For a network with n nodes, we assume that there may be up to $n(n-1)$ potential lightpaths. When b_p takes value 1, it means lightpath p^{th} is selected for the final logical topology, otherwise the p^{th} lightpath is not included in the logical topology. There are potential P lightpaths in the network, so there are P lightpath selection binary varibles in the formulation.

Route creation binary variables for lightpaths x_{pr}, y_{pr}

$$x_{pr} = \begin{cases} 1, \text{if lightpath } p \text{ uses route } r \text{ for its primary path} \\ 0, \text{otherwise} \end{cases}$$

$$y_{pr} = \begin{cases} 1, \text{if lightpath } p \text{ uses route } r \text{ for its backup path} \\ 0, \text{otherwise} \end{cases}$$

The binary variables x_{pr} (y_{pr}) determine the route for each primary path and backup path over the physical topology. If lightpath p is selected to be in the final logical topology, to protect the network from the single fiber failure, we need to find a primary and backup path and route them over the physical topology. Otherwise the variables x_{pr} (y_{pr}) take the value 0. The variables x_{pr} (y_{pr}) take the value 1 only if the lightpath p is selected in the final logical topology (i.e. b_p=1). In our study, the maximum number of alternate routes between any node-pair is $R = 3$. There are P potential lightpaths in the network with potential R routes. So, there are 2RP binary variables in our MILP formulation

Channel assignment binary variables for lightpath w_{kp}, z_{kp}

$$w_{kp} = \begin{cases} 1, \text{ if lightpath } p \text{ use the channel k for its primary path} \\ 0, \text{ otherwise} \end{cases}$$

$$z_{kp} = \begin{cases} 1, \text{ if lightpath } p \text{ use the channel k for its backup path} \\ 0, \text{ otherwise} \end{cases}$$

The binary variables w_{kp} (z_{kp}) are used to assign a wavelength channel to primary path and backup path corresponding the p^{th} lightpath. The variables w_{kp} (z_{kp}) take the value 1, only if the p^{th} lightpath is selected in the final logical topology and a wavelength channel k is assigned to the primary (backup) path corresponding to this lightpath. Otherwise, the variables w_{kp} (z_{kp}) take the value 0. There are potential P lightpaths in the network a K wavelength channels per fiber. Therefore, there are 2KP channel assignment binary variables in our formulation.

4.2.4 Continuous Variables

In this section, we define continuous variables that are used in our formulation. Even though we have used continuous variables for computational advantages, the values allowed of these variables are restricted to 0 or 1. The description of these variables is given below:

$$\delta_e^{kp} = \begin{cases} 1, \text{if primary path } p \text{ is assigned channel } k \text{ and uses edge } e \\ 0, \text{otherwise} \end{cases}$$

$$\gamma_e^{kp} = \begin{cases} 1, \text{if backup path } p \text{ is assigned channel } k \text{ and uses edge } e \\ 0, \text{otherwise} \end{cases}$$

These variables are used in the constraints to define the route and wavelength assignment of primary and backup path. The variable γ_e^{kp} (δ_e^{kp}) = 1 only if the primary (backup) path uses a route which across through edge e and a channel k is assigned to this route. There are m edges in the physical topology with each edge accommodating k wavelength channels, and P potential lightpaths to consider. So, there are $mKP(mKP)$ continuous variables δ_e^{kp} (γ_e^{kp}) for all possible values k, p, and e in δ_e^{kp} (γ_e^{kp}). However, when we use the constant d_e^{pr}, we can reduce the number of the variables used in MILP formulation. As mentioned before, we only consider the edge used in the r^{th} route of lightpath p, not all the possible edges. So the actually number of continuous variables in δ_e^{kp} (γ_e^{kp}) are less than $mKP(mKP)$.

$$\alpha_e^k = \begin{cases} 1, \text{ if at least one lightpath } p \text{ that use edge } e \text{ and channel } k \text{ on its backup path} \\ 0, \text{ otherwise} \end{cases}$$

This variable is used in the constraint to ensure that a primary path is edge-channel disjoint with respect to all backup paths. The variable takes value 1, when at least one lightpath uses edge e and channel k on its backup path. Otherwise, the variable takes value 0. The potential number of variables in α_e^k is mK for all possible values k and e.

$$\theta_{e1e2}^{kp} = \begin{cases} 1, \text{ if lightpath } p \text{ uses channel k and edge } e1 \text{ on its backup path and uses} \\ \quad \text{edge } e2 \text{ on its primary path.} \\ 0, \end{cases}$$

This variable is used in constraints to ensure that when two backup paths share a same channel on the same fiber, their corresponding primary path must be fiber disjoint. The variable takes value 1, when p^{th} backup path is assigned channel k and uses edge $e1$ and its corresponding primary path uses edge $e2$. Otherwise, the variable takes value 0. The potential number of variables in θ_{e1e2}^{kp} is m^2KP for all possible values k, p, $e1$ and $e2$. The actual number of the variables in θ_{e1e2}^{kp} is less than m^2KP by using the constant d_e^{pr}.

$$\eta_e^{kp} = \begin{cases} 1, \text{ if primary path } p \text{ uses edge } e \text{ and corresponding backup path uses} \\ \quad \text{channel } k \\ 0, \text{ otherwise} \end{cases}$$

This variable is used in the constraints to determine the number of the transmitters and receivers at each end node after the occurrence of single fiber failure. The variable takes value 1, when the p^{th} primary path uses edge e and corresponding backup path uses channel k. Otherwise, the variable takes value 0. The potential number of variables in η_e^{kp} is mKP for all possible values k, p and e. The same as above, by using the constant d_e^{pr}, the actual number of the variables in η_e^{kp} is less than mKP.

The variable f_p^{sd} is used to define the continuous flow variables that represent the amount of s – d traffic (traffic originating from s and destined for d) routed over the p^{th} lightpath. These variables are used to routing the traffic request in the traffic matrix over the all selected lightpaths

4.2.5 Constraints

In this section, we will introduce the constraints that are used in our MILP formulation. These constraints are used to define the channel and path allocation, the relationship between the primary and backup paths, the usage of the transmitters and receivers, and traffic routing over the lightpaths. We will derive the mathematical equations that represent these constraints and give detailed explanations of the equation according to their different functions.

1) **Channel and path allocation**

$$\sum_{r\in R_p} x_{p,r} - b_p = 0, \qquad \forall_p \in P \tag{1}$$

$$\sum_{r\in R_p} y_{p,r} - b_p = 0, \qquad \forall_p \in P \tag{2}$$

Constraints (1) and (2) are used to route the selected lightpath over the physical topology. Since we use WDM path protection scheme, for each selected lightpath, we need to route a primary and backup path. As mentioned before, to simplify our MILP formulation, we route our lightpath along one of three predefined routes. If a potential lightpath p is selected (b_p= 1), then $\sum_{r\in R} x_{p,r}=1$ and $\sum_{r\in R_p} y_{p,r}=1$. This means that $x_{p,r}=1$ and $y_{p,r}=1$ for only one value of r, $x_{p,r}$= 0 and $y_{p,r}$= 0 for all other value of r. This ensures that each selected is assigned exactly one route for its primary and one route for its backup path.

$$\sum_{k\in K} w_{kp} - b_p = 0, \qquad \forall_p \in P \tag{3}$$

$$\sum_{k\in K} z_{kp} - b_p = 0, \qquad \forall_p \in P \tag{4}$$

Constraints (3) and (4) are used to assign a wavelength channel for the primary and backup path of each selected lightpath. According to the wavelength continuity constraint, a lightpath should be on the same wavelength channel throughout its path. For each primary path and backup path of the selected lightpath, we only can assign a single wavelength channel. For each potential lightpath p, if it is selected (b_p=1), then $\sum_{k\in K} w_{kp}=1$ and $\sum_{k\in K} z_{kp}=1$. This means that $w_{kp}=1$ and $z_{kp}=1$ for exactly one value of the

k, and w_{kp}=0 and z_{kp}=0 for all other values of the k. This ensures the wavelength continuity constraint for each primary and backup path.

2) Corresponding primary and backup paths must be fiber-disjoint.

$$x_{p,r} + y_{p,r} - b_p \leq 0, \qquad \forall_p \in P, r = 1,2,\ldots,R \tag{5}$$

Constraint (5) ensures that corresponding primary and backup path do not use the same fiber through their route. Normally, when a connection request arrives, we use the primary path to transfer the data. When the primary path fails, the backup path will be used to transfer data. The primary path and its corresponding backup path cannot fail at the same time, so they cannot use the same fiber through their route. If a potential lightpath p is selected (b_p=1), then if primary path uses the r^{th} route, $x_{p,r}$= 1, then the backup path cannot chose the same route, $y_{p,r}$= 0. Similarly, if backup path uses the r^{th} route, $y_{p,r}$= 1, then the primary path cannot chose the same route, $x_{p,r}$= 0.

3) Each primary path is edge-channel disjoint with every other primary and backup path.

$$\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r} + w_{kp} - \delta_e^{kp} \leq 1, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{6}$$

$$\delta_e^{kp} - \sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{7}$$

$$\delta_e^{kp} - w_{kp} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{8}$$

Constraints (6)-(8) are used to define the variable δ_e^{kp}. Constraint (6) sets variable $\delta_e^{kp} \geq$ 1, if w_{kp}= 1, (i.e. primary path is assigned a wavelength channel k) and $\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r}$ = 1, (i.e. this primary path use edge e). $\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r}$=1, if the p^{th} primary path uses r^{th} route, and this route contains edge e. The constraints (7) and (8) force variable $\delta_e^{kp} \leq 1$. Therefore, the variable δ_e^{kp}= 1, if and only if the primary path p is assigned wavelength channel k and use edge e. If either condition is not satisfied, the δ_e^{kp} = 0.

$$\sum_{r \in R_p} d_e^{p,r} \cdot y_{p,r} + z_{kp} - \gamma_d^{kp} \leq 1, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{9}$$

$$\gamma_e^{kp} - \sum_{r \in R_p} d_e^{p,r} \cdot y_{p,r} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{10}$$

$$\gamma_e^{kp} - z_{kp} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{11}$$

Constraints (9)-(11) are used to define the variable $\gamma_e^{p,r}$. Constraint (9) sets variable $\gamma_e^{p,r} \geq$ 1, if z_{kp}= 1, (i.e. backup path is assigned a wavelength channel k) and $\sum_{r \in R_p} d_e^{p,r} \cdot y_{p,r}$ = 1, (i.e. this backup path use edge e). $\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r}$=1, if the p^{th} primary path uses r^{th} route, and this route contains edge e. The constraints (10) and (11) force variable $\gamma_e^{p,r} \leq 1$. Therefore, the variable $\gamma_e^{p,r}$= 1, if and only if the backup path p^{th} is assigned wavelength channel k and use edge e on its primary path. If either condition is not satisfied, the δ_e^{kp} = 0.

$$\gamma_e^{kp} - \alpha_e^{k} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{12}$$

$$\alpha_e^k \leq 1, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \qquad (13)$$

$$\alpha_e^k - \sum_{p=1}^{P} \gamma_e^{kp} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \qquad (14)$$

Constraints (12) - (14) are used to define the variable α_e^k. The constraint (12) set $\alpha_e^k \geq$ 1, whenever the $\gamma_e^{p,r}$ =1. The constraint (13) set the $\alpha_e^k \leq 1$. These two constraint ensure the α_e^k= 1, when there is a backup path is assigned channel k and use edge e. Constraint (14) sets $\sum_{p=1}^{P} \gamma_e^{kp} \geq 1$, whenever α_e^k= 1, which means that there may be more than one backup path is assigned channel k and use the same edge e. In other words, α_e^k= 1, if there is at least one lightpath p^{th} that use channel k and edge e on its backup path. Otherwise $\alpha_e^k = 0$.

$$\sum_{p=1}^{P} \delta_e^{kp} + \alpha_e^k \leq 1, \qquad \forall e \in E, \forall k \leq K, \qquad (15)$$

Constraint (15) is used to ensure that each primary path is edge-channel disjoint with every other primary and backup path. When $\alpha_e^k = 0$, $\sum_{p=1}^{P} \delta_e^{kp} \leq 1$, which means that for all primary paths using edge e, at most one of them can be assigned wavelength channel. This ensures that each primary path is edge-channel disjoint with every other primary path. This constraint also implies that $\sum_{p=1}^{P} \delta_e^{kp}$ and α_e^k cannot be the 1 at the same time, which ensures that the primary path is also edge-channel disjoint with any other backup path.

4) Two backup paths sharing a channel and edge ⇒ corresponding primary paths fiber-disjoint

$$\gamma_{e1}^{kp} + \sum_{r\in R_p} d_{e2}^{p,r}\cdot x_{p,r} - \theta_{e1e2}^{kp} \le 1, \qquad \forall k\in K, \forall p\in P, \forall e1, e2\in E, e1\ne e2, \qquad \textbf{(16)}$$

$$\theta_{e1e2}^{kp} - \gamma_{e1}^{kp} \le 0, \qquad \forall k\in K, \forall p\in P, \forall e1, e2\in E, e1\ne e2, \qquad \textbf{(17)}$$

$$\theta_{e1e2}^{kp} - \sum_{r\in R_p} d_{e2}^{p,r}\cdot x_{p,r} \le 0, \qquad \forall k\in K, \forall p\in P, \forall e1, e2\in E, e1\ne e2, \qquad \textbf{(18)}$$

Constraints (16)-(18) are used to define the variable θ_{e1e2}^{kp}. Constraint (16) sets variable $\theta_{e1e2}^{kp} \ge 1$, if $\gamma_{e1}^{kp} = 1$, which means that for the p^{th} lightpath, its backup path is assigned a wavelength channel k and use the edge $e1$ and $\sum_{r\in R_p} d_{e}^{p,r}\cdot x_{p,r} = 1$, which means that its corresponding primary path uses edge $e2$. The constraints (17) and (18) force variable $\theta_{e1e2}^{kp} \le 1$. Therefore, the variable $\theta_{e1e2}^{kp} = 1$, if and only if the backup path is assigned wavelength channel k and use edge $e1$ and it corresponding primary path use edge $e2$. If either condition is not satisfied, the $\theta_{e1e2}^{kp} = 0$.

$$\sum_{p\in P} \theta_{e1e2}^{kp} \le 1, \qquad \forall k\in K, \forall p\in P, \forall e1, e2\in E, e1\ne e2, \qquad \textbf{(19)}$$

Constraint (19) guarantees that, when two backup paths share same channel k on same edge $e1$, their corresponding primary paths can not use the same edge $e2$. This ensures that for two backup paths sharing a channel and edge, their corresponding primary paths must be fiber-disjoint.

5) Constraints corresponding to transmitters and receivers at each node

The number of transmitters and receivers at a node directly restrict the number of lightpaths originating from or terminating at that node. Constraints corresponding to transmitters and receivers at each node are explained below. We consider two cases.

Case 1: No fiber fails.

$$\sum_{\{p:l(p)=u\}} w_{kp} \leq r_u^k, \qquad \forall k \in K, u \in N \tag{20}$$

$$\sum_{\{p:o(p)=u\}} w_{kp} \leq t_u^k, \qquad \forall k \in K, u \in N \tag{21}$$

Constraint (20) and (21) are used to ensure that the number of primary paths that use wavelength channel k and originate from ($o(p)=u$) or terminating at ($l(p)=u$) node u, should be less than the given number of transmitters (t_u^k) or receivers (r_u^k) at node u, which are tuned to wavelength channel k.

Case 2: Suppose a fiber fails and this destroys several primary paths

$$\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r} + z_{kp} - \eta_e^{kp} \leq 1, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{22}$$

$$\eta_e^{kp} - \sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{23}$$

$$\eta_e^{kp} - z_{kp} \leq 0, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{24}$$

Constraints (22) – (24) are used to define the variable η_e^{kp}. Constraint (22) sets variable $\eta_e^{kp} \geq 1$, whenever $\sum_{r \in R_p} d_e^{p,r} \cdot x_{p,r} = 1$, (i.e. primary path use edge e), and $z_{kp} = 1$, (i.e. backup path is assigned a wavelength channel k). The constraints (23) and (24) force variable $\eta_e^{kp} \leq 1$. Therefore, the variable $\eta_e^{kp} = 1$, if and only if the p^{th} primary path uses edge e and its corresponding backup path is assigned wavelength channel k. If either condition is not satisfied, the $\eta_e^{kp} = 0$.

$$\sum_{\{p:l(p)=u\}} \left[w_{kp} - \delta_e^{kp} + \eta_e^{kp} \right] \leq r_u^k, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{25}$$

$$\sum_{\{p:o(p)=u\}} \left[w_{kp} - \delta_e^{kp} + \eta_e^{kp} \right] \leq t_u^k, \qquad \forall e \in E, \forall k \in K, \forall p \in P, \tag{26}$$

Constraints (25) and (26) are used to ensure that the total number of lightpaths, including the working primary paths and the backup paths that replace the unusable primary paths, originating from (terminating at) node u and using wavelength k cannot exceed the number of transmitters (receivers) at node u tuned to k. In constraint (25) and (26), $\sum_{\{p:o(p)=u\}} w_{kp}$ ($\sum_{\{p:l(p)=u\}} w_{kp}$) provide the number of the primary paths that use wavelength channel k and originate from ($o(p) = u$) or terminate at ($l(p) = u$) node u before fiber failure. Suppose edge e fails, $\sum_{\{p:o(p)=u\}} \delta_e^{kp}$ ($\sum_{\{p:l(p)=u\}} \delta_e^{kp}$) provides the number of primary paths that were using channel k, originating from (terminating at) node u, which are now destroyed. Similarly, $\sum_{\{p:o(p)=u\}} \eta_e^{kp}$ ($\sum_{\{p:l(p)=u\}} \eta_e^{kp}$) provides the number of backup paths that were assigned channel k, originating from (terminating at) node u, and now replacing these destroyed paths. Then the total number of lightpaths originating from (terminating at) node u and using channel k after fiber failure is $\sum_{\{p:o(p)=u\}} \left[w_{kp} - \delta_e^{kp} + \eta_e^{kp} \right]$ ($\sum_{\{p:l(p)=u\}} \left[w_{kp} - \delta_e^{kp} + \eta_e^{kp} \right]$), which must be less than t_u^k (r_u^k).

6) **Traffic flows and constrains on the logical topology.**

$$f_p^{sd} - b_p \lambda^{sd} \leq 0, \qquad \forall p \in P, \forall s,d \in N, s \neq d, \qquad (27)$$

Constraint (27) is used to define the traffic flows between each node pair. If the p^{th} lightpath is selected (b_p=1), then the amount of traffic originating from s to d (f_p^{sd}) must be less than the total amount of traffic between node pair s-d.

$$\varepsilon b_p - \sum_{s \neq d} f_p^{sd} \leq 0, \qquad \forall p \in P, \forall s,d \in N, s \neq d, \qquad (28)$$

Constraint (28) is used to ensure that the total amount of traffic on any selected lightpath cannot be less than ε. This constraint is used to eliminate logical edges that carry very little traffic.

$$\sum_{\{p:o(p)=i\}} f_p^{sd} - \sum_{\{p:l(p)=i\}} f_p^{sd} = \begin{cases} \lambda^{sd}, \text{ if } i=s \\ -\lambda^{sd}, \text{ if } i=d \\ 0, \text{ otherwise} \end{cases} \qquad \forall s,d,i \in N, s \neq d, \qquad (29)$$

Constraint (29) is a set of flow conservation constraints, which are used to route the traffic over the lightpaths between the node pair s and d. For any node, if $i = s$, i is source node, the total traffic amount on all lightpaths between node pair s and d originating from the source node i will be the λ^{sd}. If $i = d$, i is destination node, the total traffic amount on all lightpaths between node pair s and d terminating at destination node will be λ^{sd}. If i is intermediate node, then the total amount traffic on all lightpaths coming in the node i will be equal to the amount traffic go out of it.

$$\sum_{s \neq d} f_p^{sd} - F_{\max} \leq 0, \qquad \forall p \in P, \forall s,d \in N, s \neq d, \qquad (30)$$

Constraint (30) is used to ensure that the maximum amount of traffic flow on any lightpath is less than F_{max}..

$$\sum_{s \neq d} f_p^{sd} \leq 1, \qquad \forall p \in P, \forall s,d \in N, s \neq d, \qquad (31)$$

Constraint (31) is used to ensure that the total amount of traffic flow on any lightpath is not greater than 1. In other words, the maximum capacity of a lightpath is 1.

4.2.6 Objective Function

The objective function defined in our MILP formulation is:

Minimize $F_{\max}$

$F_{\max}$ is defined as the maximum amount of traffic flow on any lightpath. In our formulation, we have normalized the traffic flow on any lightpath with respect to the maximum amount of data that can be transmitted over a single lightpath. The objective function of the formulation is to minimize the network congestion $F_{\max}$.

4.3 MILP Formulation Implementation

We use the CPLEX, a well-known and powerful linear programming tool, to solve this MILP formulation for different networks [IL01]. However, CPLEX is not able to handle a generalized formulation, with composite constraints as given before. In our study, we implement a C program to automatically generate a set of individual constraints in LP (Linear Program) format, which can be understood by CPLEX.

The C program takes the set of network nodes, the set of physical edges, the number of channels per fiber, the number of transmitters and receivers per wavelength per node, and the traffic matrix as input written in an input file. The output of the C program is written to an output file, which include the objective function, all individual constraints, and bounds to all decision variables. CPLEX can read this output file, run the computation and obtain the solution.

Following shows our C program to generate the output file read by the CPLEX.

Step1: Read the network specification from an input file.

Step2: Create the edge array E for all the physical edges in the network

Step3: Create the traffic matrix array A based on the given traffic matrix.

Step4: Create lightpath array P for all potential lightpaths.

Step5: Create transmitter and receiver array T and R based on the given number of transmitters and receivers per wavelength per node.

Step6: Create 3 shortest paths, and save then in path array.

Step7: Form the objective function and write to the output file.

Step8: Generate all individual constrains for each composite constraint and write them to the output file.

Step9: Generate the upper and lower bounds for each decision variable and write them to the output file.

Chapter 5 Experiment and Results

In this chapter, we explain the experiments carried out for testing our complete MILP formulation and analyze the results of these experiments. Even though we simplify our MILP formulation by reducing the number of integer variables used in the formulation, this formulation is still very complicated and only can be solved for small to medium-sized networks. In our experiments, we use three physical topologies with different number of wavelength channels per fiber, and with different traffic matrices.

For each set of experiments, we selected a specific physical topology and varied the traffic matrix as well as the number of available wavelengths carried by each fiber. For each physical topology, the traffic matrices were selected to reflect different load conditions. They were classified as low, medium or high load, based on the total amount of traffic presented to the network (obtained by adding all the entries of the traffic matrix). For each set of experiments, we assumed that there was one transmitter and one receiver per wavelength at each node.

Our MILP formulation generated the logical topology with the path protection for single fiber failure. The results of our experiments for the different networks are shown below in Tables 5.1 – 5.3. In these tables, the traffic matrix T1 represent low load condition, the traffic matrix T2 represent medium load condition, and the traffic matrix T3 represents high load condition. The traffic matrices for the different networks are shown in Appendix A.

5.1 Experiments with a Four Nodes network

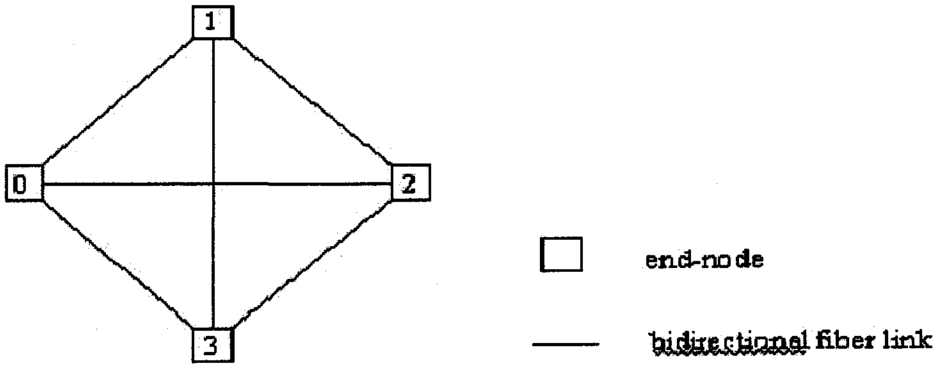


Figure 5.1 Four Nodes Network

In figure 5.1, we give a four nodes network with 6 bidirectional fiber links. To test the network under the different traffic load conditions, we give three traffic matrices. For each traffic matrix, we test the network with different number of channels carried by each fiber. The result of the experiments for this four nodes network is shown in table 5.1.

Traffic matrix	#of wavelengths/fiber	# of constraints	Congestion	Solution time (sec)
T1	4	5768	0.08	5.54
	8	11224	0.08	7.52
	16	22135	0.08	9.97
	32	43960	0.08	88.86
	64	87608	0.08	134.22
T2	4	5768	0.55	7.95
	8	11224	0.55	5.43
	16	22135	0.55	9.06
	32	43960	0.55	22.64
	64	87960	0.55	71.30
T3	4	5768	0.875	2.00
	8	11224	0.875	4.04
	16	22135	0.875	4.81
	32	43960	0.875	11.08
	64	87608	0.875	46.45

Table 5.1 Experiment results with a four nodes network

5.2 Experiments with a Six Nodes Network

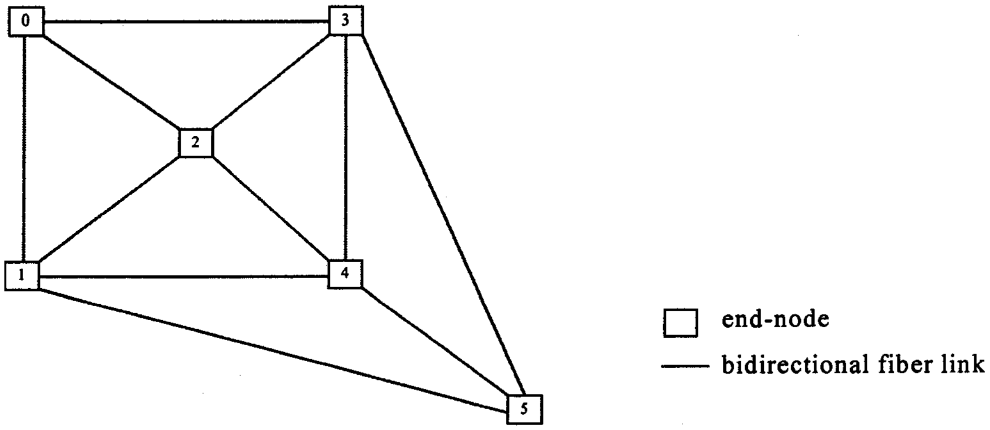


Figure 5.2 Six Nodes Networks

In figure 5.2, we give a six nodes network with 11 bidirectional fiber links. As before, to test the network under the different traffic load conditions, we give three traffic matrixes. For each traffic matrix, we test the network with different number of channels supported by each fiber edges. The result of the experiments for this six nodes network is shown in table 5.2.

Traffic matrix	#of wavelength/fibr	# of constraint	Congestion	Solution time
T1	8	33460	0.4	831.05
	16	65540	0.4	261.79
	32	129700	0.4	595.21
	64	258020	0.4	1203.73
T2	8	33460	0.5167	509.13
	16	65540	0.5167	243.64
	32	129700	0.5167	198.10
	64	258020	0.5167	1268.16
T3	8	33460	0.87	230.05
	16	65540	0.87	144.18
	32	129700	0.87	174.36
	64	258020	0.87	482.05

Table 5.2 Experiment results with six nodes network

5.3 Experiments with Eight Nodes Network

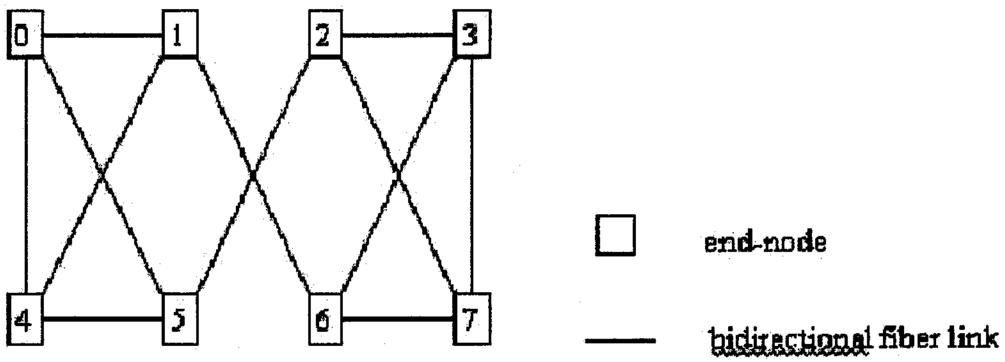


Figure 5.3 Eight nodes Network

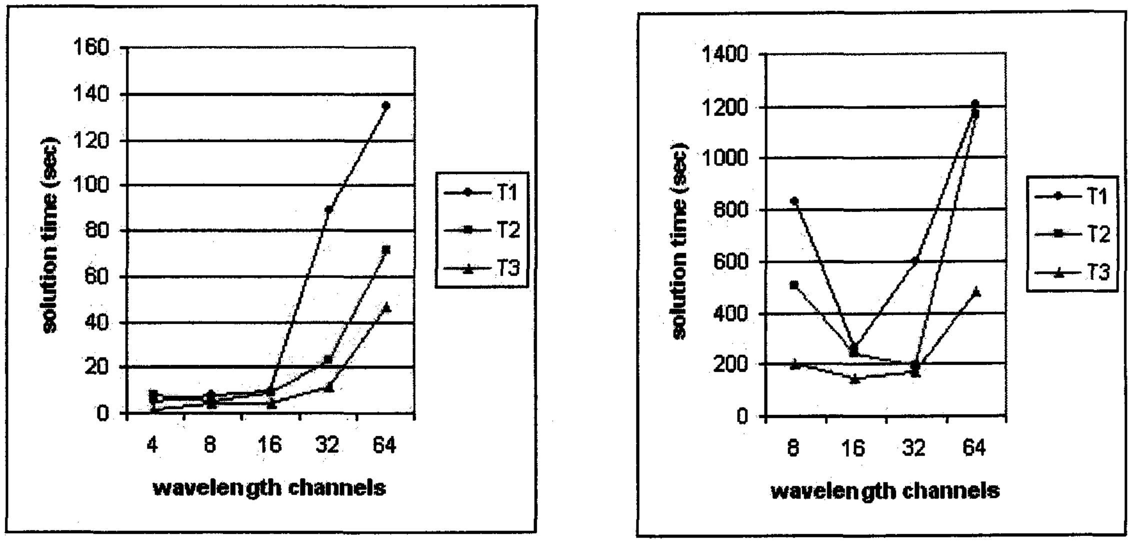
Figure 5.3 shows an eight nodes network with 12 bidirectional fiber links. Similarly, to test the network under the different traffic load conditions, we give three traffic matrixes. For each traffic matrix, we test the network with different number of channels carried by each fiber edges. The result of the experiments for this eight nodes network is shown in table 5.3.

Traffic matrix	#of wavelength/fibr	# of constraint	Congestion	Solution time
T1	32	266672	0.3929	3909.09
	64	529200	0.3929	7766.59
T2	32	266672	0.6810	3844.37
	64	529200	0,6810	7538.56
T3	32	266672	0.8857	3153.80
	64	529200	0.8857	5803.42

Table 5.3 Experiment results with eight nodes network

5.4 Discussion of the Experimental Results

Tables 5.1 – 5.3 show the results of our experiments with different networks. They indicate that the solution time of the formulation is related to the number of wavelength channels supported by each fiber and the given traffic matrix. Figure 5.1 below show the analysis of experiment results of a four nodes network and six nodes network.



(a) Four nodes network

(b) Six nodes network

Figure 5.4 Experiment result analysis

From figure 5.1, we can see that the solution time of our MILP formulation is related to the number of wavelength channels carried by each fiber. When we increase the number of the channels, it becomes easier to allocate channels to primary and backup lightpaths. This can initially reduce the time to get the solution. However, as the number of the channels increase, the number of the variables and the number of constraints in the formulation also increase significantly. After a certain point increasing the number of channels provides no additional benefit, it simply increases the complexity of the formulation. This leads to an increase in the solution time. For example, from figure 5.1(b), we can see when each fiber supports 8 wavelength channels, the solution time of the six nodes network are 831.05 sec for traffic matrix T1, 509.73 sec for traffic matrix T2, and 230 sec for traffic matrix T3. When we increase the number of the channels to 16, the solution time decreases. However, when we increase the number of the channels to 32 and 64, the number of the variables in the formulation increases considerably, and the time to get the solution becomes longer.

Figure 5.1 also indicates that the solution time of the MILP formulation depends on the given traffic matrix. With the high load traffic matrices, each node pair can accommodate more traffic. So the chances of multi-hop communications decrease considerably. Therefore, if enough wavelengths and transmitters are available, the traffic will simply be routed by a single-hop, as this corresponds to shorter solution time. For example from the figure 5.1 (a) and (b), we can see that when each physical fiber supports the same number of the wavelength channel, the time for getting the solution became longer from low matrix load T1 to high matrix load T3.

5.5 Complexity Analysis

In this section, we measure the complexity of the MILP formulation in terms of three parameters - the number of integer variables, the number of continuous variables and the number of constraints. For our complexity analysis, we consider an arbitrary physical network with *N* nodes *E* edges, *K* channels per fiber, and $P = N (N\text{-}1)$ potential logical edges. We then determine the number of integer variables, continuous variables and constraints in our formulation and compare these values to the corresponding values for the MILP formulation (ILP1) given in [SRM02]. The most important factor affecting the complexity of the MILP is the number of integer (binary) variables in the formulation, since the complexity increases exponentially with the number of binary variables.

	Our Formulation	ILP1
# of integer variables	$P[2R+2K+1]$	$2E+EK+P[R^2K+RK+1]$
# of cont. vars	$[3E+E^2]KP+EK+P^2$	$P^2[1+R]$
# of constraints	$2P^2+P[10EK+2K+R+N+6]+EK+4NK$	$P[RK+N+4]+K[E^2+2N+2EN+7E]+3E$

Table 5.4: Comparison of number of variables and constraints

We can see from Table 5.4, that the number of integer variables increase much more slowly in our formulation. The number of continuous variables and the number of constraints is higher in our formulation compared to that in [SRM02]. This is because we have deliberately defined some variables as continuous variables, even though they could have been formulated as binary variables. For example, δ_e^{kp}, α_{ke}, γ_e^{kp}, θ_{e1e2}^{kp} and η_{ij}^{kp} are all continuous variables. However, the possible values for these variables are always restricted to 0 or 1, by the constraints used in defining these variables. Furthermore, the values for these variables are completely defined, by setting the values of the integer variables. Defining the above variables as continuous variables requires us to put additional constraints.

No. of nodes	No. of Wavelength	No. of integer variables	
		Ours	ILP1
4	8	180	1264
	16	468	2496
	32	852	4960
14	8	4186	18074
	16	7098	35882
	32	12922	72398
20	8	8740	37660
	16	14820	74780
	32	26980	149020

Table 5.5: Comparison of number of integer variables

Table 5.5 illustrates how quickly the number of integer variables increase with the size of the network and the number of available wavelengths per fiber.

Chapter 6: Summary

In our thesis, we proposed a complete MILP formulation to solve the fault-tolerant logical topology design problem. The design process had to take into account the underlying physical topology, the amount and distribution of traffic to be handled by the network and resource constraints on the number of available optical components at each node and the capacity of the optical fibers. The objective of the formulation is to minimize the congestion of the network, which is defined as the maximum traffic flow on any lightpath.

In this thesis, the proposed MILP formulation is used to design a fault tolerant logical topology and the routing scheme over the logical topology for a given WDM network and traffic matrix. We also use the shared path protection technique to provide protection against any single fiber failure. Determining a primary path and a backup path and the wavelengths for each lightpath in the logical topology can successfully accomplished this.

Logical topology design with shared path protection is a very complicated problem. The main complexity of the MILP formulation is the number of the integer variables used in the formulation. To simplify our MILP formulation, we need to reduce the number of the integer variables used in the formulation. In this thesis, we achieve this by creating three edge-disjoint shortest paths for every node pair in the network. For each selected lightpath that used to constitute the final logical topology, we choose one of these three paths as the route for the primary path and another as the route for the backup path instead of choosing from all the alternate routes in the network. This greatly reduces the number of integer variables used in the formulation, since we no longer need to search for routes over the physical topology. Even with this simplification, the formulation is still not feasible for large networks.

6.1 Future Work

Though the new MILP formulation proposed in our thesis can describe our logical topology design problem more efficiently, it still computational intractable for large networks. As mentioned before, logical topology design is actually a combined problem of selecting lightpaths and routing and wavelength assignment (RWA). In this thesis, our approach solves them together, this makes problem complicated. To simplify our problem, we can divide the problem into two separate steps. The first step, would consider the selection of lightpaths that constitute the logical topology. The selection of lightpath is restricted by the number of transmitters and receivers at each end node and the given traffic matrix. The second step, would consider routing and wavelength assignment of lightpaths selected in the previous step. Thus, instead of using one single MILP formulation, as proposed in our thesis, the problem can be decomposed into two simpler MILP formulations. The new approach should be computationally much faster. But, the drawback is that, if the two phases are separated, there is no guarantee that the set of selected lightpaths can be successful routed over the physical topology. Therefore, we will be trading off quality of the solution for speed.

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Appendix A: Traffic Matrix

The traffic matrix T1 represent low load condition, the traffic matrix T2 represent medium load condition, and the traffic matrix T3 represent high load condition. They are shown below.

Traffic matrices for four nodes network:

$$\mathrm{T1}=\begin{pmatrix} 0.00 & 0.015 & 0.03 & 0.07 \\ 0.08 & 0.00 & 0.05 & 0.09 \\ 0.07 & 0.02 & 0.00 & 0.06 \\ 0.09 & 0.07 & 0.04 & 0.00 \end{pmatrix} \qquad \mathrm{T2}=\begin{pmatrix} 0.00 & 0.60 & 0.20 & 0.30 \\ 0.50 & 0.00 & 0.10 & 0.60 \\ 0.40 & 0.70 & 0.00 & 0.30 \\ 0.70 & 0.20 & 0.60 & 0.00 \end{pmatrix}$$

$$\mathrm{T3}=\begin{pmatrix} 0.00 & 0.80 & 0.60 & 0.90 \\ 0.90 & 0.00 & 0.75 & 0.80 \\ 0.80 & 0.70 & 0.00 & 0.60 \\ 0.70 & 0.95 & 0.90 & 0.00 \end{pmatrix}$$

Traffic matrices for six nodes networks:

$$\mathrm{T1}=\begin{pmatrix} 0.00 & 0.10 & 0.20 & 0.30 & 0.60 & 0.10 \\ 0.10 & 0.00 & 0.20 & 0.10 & 0.10 & 0.70 \\ 0.90 & 0.10 & 0.00 & 0.30 & 0.10 & 0.10 \\ 0.10 & 0.20 & 0.80 & 0.00 & 0.30 & 0.20 \\ 0.10 & 0.30 & 0.10 & 0.60 & 0.00 & 0.10 \\ 0.20 & 0.10 & 0.20 & 0.10 & 0.80 & 0.00 \end{pmatrix} \qquad \mathrm{T2}=\begin{pmatrix} 0.00 & 0.60 & 0.20 & 0.30 & 0.70 & 0.10 \\ 0.50 & 0.00 & 0.10 & 0.60 & 0.50 & 0.70 \\ 0.40 & 0.70 & 0.00 & 0.30 & 0.10 & 0.50 \\ 0.70 & 0.20 & 0.60 & 0.00 & 0.30 & 0.20 \\ 0.10 & 0.40 & 0.10 & 0.70 & 0.00 & 0.50 \\ 0.20 & 0.50 & 0.40 & 0.10 & 0.90 & 0.00 \end{pmatrix}$$

$$T3=\begin{pmatrix} 0.00 & 0.80 & 0.60 & 0.90 & 0.70 & 0.85 \\ 0.90 & 0.00 & 0.75 & 0.80 & 0.65 & 0.70 \\ 0.80 & 0.70 & 0.00 & 0.60 & 0.90 & 0.60 \\ 0.70 & 0.95 & 0.90 & 0.00 & 0.80 & 0.55 \\ 0.80 & 0.60 & 0.85 & 0.70 & 0.00 & 0.90 \\ 0.95 & 0.85 & 0.80 & 0.85 & 0.90 & 0.00 \end{pmatrix}$$

Traffic matrices for eight nodes network:

$$T2 = \begin{pmatrix} 0.00 & 0.30 & 0.60 & 0.80 & 0.50 & 0.10 & 0.70 & 0.60 \\ 0.75 & 0.00 & 0.50 & 0.70 & 0.40 & 0.60 & 0.10 & 0.90 \\ 0.60 & 0.70 & 0.00 & 0.50 & 0.60 & 0.75 & 0.40 & 0.80 \\ 0.40 & 0.10 & 0.60 & 0.00 & 0.80 & 0.50 & 0.10 & 0.60 \\ 0.30 & 0.70 & 0.55 & 0.90 & 0.00 & 0.60 & 0.50 & 0.10 \\ 0.80 & 0.60 & 0.50 & 0.60 & 0.80 & 0.00 & 0.70 & 0.40 \\ 0.50 & 0.50 & 0.60 & 0.60 & 0.70 & 0.40 & 0.00 & 0.80 \\ 0.60 & 0.60 & 0.45 & 0.55 & 0.80 & 0.30 & 0.90 & 0.00 \end{pmatrix}$$

$$T1 = \begin{pmatrix} 0.00 & 0.10 & 0.20 & 0.30 & 0.60 & 0.10 & 0.20 & 0.10 \\ 0.10 & 0.00 & 0.20 & 0.10 & 0.10 & 0.70 & 0.30 & 0.20 \\ 0.90 & 0.10 & 0.00 & 0.30 & 0.10 & 0.10 & 0.10 & 0.40 \\ 0.10 & 0.20 & 0.80 & 0.00 & 0.30 & 0.20 & 0.20 & 0.10 \\ 0.10 & 0.30 & 0.10 & 0.60 & 0.00 & 0.10 & 0.15 & 0.10 \\ 0.20 & 0.10 & 0.20 & 0.10 & 0.80 & 0.00 & 0.10 & 0.30 \\ 0.30 & 0.20 & 0.10 & 0.10 & 0.60 & 0.10 & 0.00 & 0.20 \\ 0.10 & 0.60 & 0.20 & 0.10 & 0.25 & 0.10 & 0.20 & 0.00 \end{pmatrix}$$

$$T3 = \begin{pmatrix} 0.00 & 0.70 & 0.90 & 0.80 & 0.50 & 0.95 & 0.90 & 0.60 \\ 0.95 & 0.00 & 0.85 & 0.95 & 0.85 & 0.90 & 0.80 & 0.90 \\ 0.80 & 0.90 & 0.00 & 0.90 & 0.90 & 0.85 & 0.95 & 0.80 \\ 0.90 & 0.80 & 0.70 & 0.00 & 0.80 & 0.90 & 0.80 & 0.90 \\ 0.85 & 0.70 & 0.90 & 0.90 & 0.00 & 0.80 & 0.70 & 0.80 \\ 0.80 & 0.90 & 0.90 & 0.80 & 0.90 & 0.00 & 0.90 & 0.70 \\ 0.90 & 0.70 & 0.80 & 0.90 & 0.70 & 0.85 & 0.00 & 0.90 \\ 0.60 & 0.90 & 0.95 & 0.85 & 0.90 & 0.70 & 0.90 & 0.00 \end{pmatrix}$$

Appendix B: Glossary

CPLEX - C Programming Language + simpEX

ILP - Integer Linear Programming

IP – Internet Protocol

LP - Linear Programming

MILP - Mixed-Integer Linear Programming

OXC - Optical Cross-Connect

PILP - Pure Integer Linear Programming

QoS - Quality of Service

RWA - Routing & Wavelength Assignment

WAN - Wide Area Network

WADM – Wavelength Add-Drop Multiplexer

WDM - Wavelength Division Multiplexing

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