An efficient shared path protection based on quality of service in WDM networks.

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An Efficient Shared Path Protection Based on Quality of Service in WDM Networks

By
Zhongwei Hu

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

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January 2003

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Abstract

With the explosive growth of the Internet in the past decade, survivability and high-bandwidth have become the most critical characteristics for networks. Determining the most efficient and reliable network configuration is a significant challenge in current optical network research. WDM (Wavelength Division Multiplexing) has become one of the most important features of optical networks because of its highly improved utilization of network capacity. The design of WDM networks can be analyzed from two perspectives: Network Design, and Routing & Wavelength Assignment (RWA). Network design includes physical topology design and configuration design. Routing and Wavelength Assignment (RWA) involves mapping lightpaths into the physical topology and assigning wavelength to these lightpaths. In this thesis, we concentrate on RWA, and propose a new formulation for dynamic lightpath allocations in fault-tolerant optical networks. We use WDM shared-path protection to achieve fault tolerance. Our formulation can accommodate three different qualities of service (QoS), each requiring a different amount of resources. We generate an efficient MILP formulation for dynamic lightpath allocation based on the QoS, and show through simulations, that it can be used for a practical-sized WDM networks.

Keywords

WAN, Survivability, Optical Networks, Optimization, RWA, WDM, Wavelength, QoS, Restoration scheme, Protection scheme, Shared-Path Protection, Dedicated-Path Protection, Static allocation scheme, Dynamic allocation scheme, Primary path, Backup path, LP, MILP, CPLEX, NSFNET, ARPANET.
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Chapter 1. Introduction

1.1. Background

Optical fiber communications were originally developed for the voice phone system before the 1990s. With the explosive growth of the Internet since the mid 1990s, the demand for network bandwidth has been growing at a rapid rate. Recent observers found that the Internet traffic was approximately doubling each year [1]. Fiber-optic networks have composed the main infrastructure to provide communication for businesses, government, military, as well as other fields. In United States, the data traffic in major carriers has now overtaken voice traffic [2]. Table 1.1 shows the traffic on Internet backbones in U.S. in each December from 1996 to 2000 [1].

(Note: 1 Terabytes = 1,099,511,627,776 bytes = 1024 gigabytes)

<table>
<thead>
<tr>
<th>Year</th>
<th>Terabytes / month</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>1,500</td>
</tr>
<tr>
<td>1997</td>
<td>4,000</td>
</tr>
<tr>
<td>1998</td>
<td>8,000</td>
</tr>
<tr>
<td>1999</td>
<td>16,000</td>
</tr>
<tr>
<td>2000</td>
<td>35,000</td>
</tr>
</tbody>
</table>

Table 1.1. Internet backbones traffic in US [1]

To satisfy the network request, millions of miles fiber-optic cables have been laid out in global and nationwide areas. However, the longer the networks, the greater their risks. Therefore, survivable high-capacity networks are required in building the worldwide network to avoid the most disastrous effects. Also, cost efficiency becomes another
critical aspect when building the fiber-optic network globally. People have been trying to seek the most efficient network solution. To reduce the complexity of this problem, it could be analyzed from two aspects: physical network design, and routing & wavelength assignment (RWA) [3].

1.1.1. Physical Network Design

Physical network design includes physical topology design and configuration design [3].

The *physical* topology is defined by the set of nodes and the fibers connecting them [4]. The *logical* topology is defined by the set of nodes and lightpaths connecting the nodes. Each lightpath can traverse several physical edges or fibers. The physical topology deals with nodes and the real connection link – fiber, and the logical topology deals with nodes and the logical link – lightpaths [4].

A lightpath is an end-to-end optical communication channel in the network, implemented by assigning a unique wavelength throughout the path, to provide a circuit-switched interconnection between a source node and a destination node [5, 6, 7]. Data transmitted through a lightpath do not need wavelength conversion or electronic processing at the intermediate nodes. Hence, lightpaths enable an efficient utilization of the optical bandwidth in WDM networks. Also, lightpaths can reduce electronic processing delay at the intermediate nodes, therefore, improving reliability and the quality of the services provided to data communication [8].
The physical topology design is about the determination of the number of optical cross-connects (OXC) [9] and their interconnectivity. The network configuration design is concerned with the determination of the size of OXC, the number of fibers and the set of lightpaths [3].

Both concepts involve optical cross-connects (OXC). Optical cross-connects is an important routing and switching element in backbone wavelength-division multiplexed (WDM) networks. An optical cross-connect (OXC) can switch the optical signal on a WDM channel from an input port to an output port without requiring the signal to undergo any optoelectronic conversion [10]. OXC enable optical networks to be reconfigurable on a wavelength-by-wavelength basis to match changing traffic patterns and to recover from network failures [9, 11].

1.1.2. Routing and Wavelength Assignment (RWA)

RWA problem for various physical network topologies has been addressed in [12, 13, 14, 15, 16, 17]. We can describe a RWA problem as follows: given a set of lightpaths that need to be established on the network, and given a constraint on the number of wavelengths, we need to determine the suitable routes and the wavelengths that should be assigned to the lightpaths so that the maximum number of lightpaths might be established (or the minimum number of required wavelengths is needed) [17, 18].

This thesis concentrates on the RWA problem for dynamic lightpath allocation, which can be defined as an optimization problem in a number of ways to determine the route
and the channel number for each lightpath. For example, (1) establish all lightpaths using a minimum number of wavelengths, (2) establish all lightpaths using a minimum number of path lengths, (3) maximize the number of lightpaths established subject to a constraint on the number of wavelengths and/or path lengths [18].

1.2. Motivation

In the current world, businesses are becoming increasingly dependent on the reliable and continuously available high-speed network for various common needs [2]. Designing more efficient, reliable, high-speed networks has become a critical research area in the past two decades. The advent of WDM in optical networks has significantly increased the utilization of the bandwidth on a single fiber. An optimized routing algorithm over a WDM network can achieve better performance (e.g. establish the maximum number of lightpaths) with less network resources (e.g. channels).

In our research, we develop a new efficient shared-path protection scheme based on the quality of service (QoS) in WDM networks. Connections requiring different levels of service require different amount of resources. Existing lightpath allocation algorithms do not consider QoS, they typically focus on how to route along the shortest path with valid wavelengths. Our formulation considers both RWA and QoS. This concept helps to reduce the idle network resources in a general protection scheme WDM network.

In addition, traditional approach of logical topology design is very time consuming. The main drawback is that the number of constraints grows rapidly with the size of the
network, which makes the approach become infeasible even for medium size network [61, 62]. Our approach reduces the time consuming problem by limiting the number of constraints in our formulation.

1.3. Problem Statement

Our research concentrates on the protection scheme and dynamic lightpath allocation in the survivable WDM networks. In protection-based schemes, a primary and backup lightpath is created for each connection during call setup. In dynamic lightpath allocation scheme, the lightpaths and channels are created on demand and taken down when the communication is over. We have implemented an efficient network resource allocation scheme based on three different levels of quality of services (QoS) for a new connection request. Each of the three different levels of service requires a different amount of network resources. Our formulation tries to minimize the amount of resource allocated to a connection by finding the shortest route with valid wavelength for each path. We also try to reduce the amount of idle network resources in the protection scheme by utilizing idle backup paths for low-priority connections. For instance, a level-2 (the highest priority) service requires a primary path and backup path to be setup when the call is established. The backup path is idle when there is no failure in the corresponding primary path. A low priority (level-0) connection can use the resources of the idle backup path under fault-free conditions. This increases resource utilization in the network. When a failure is detected in the level-2 primary path, its backup path can take the resources back from the existing level-0 primary path, which means the level-0 path is taken down and the level-2’s backup path is activated.
We simulate our formulation by converting it into a mixed integer linear programming (MILP) problem in LP format and optimizing in ILOG CPLEX 7.5 [56]. The network request for a new connection must specify the source and destination nodes, as well as the priority level of service. Our formulation will result in an efficient solution to allocate the primary path and its backup path (if necessary) for the new communication request. The total optical resources needed for the new connection must be minimized. The optimization problem must be solved in real-time for practical-sized networks.

1.4. Approach

Our objective is to minimize the total cost for the primary path and its backup path (if necessary), for the new required connection subject to certain physical constraints. We assume that there may already be a number of pre-existing connections in the network.

The main steps of the approach are given below:

1) Identify all the physical network topological constraints.

2) Convert above topological constraints into the mathematical constraints.

3) Convert these mathematical constraints into MILP problem in LP format.

4) Solve above LP format MILP problem by implementing in ILOG CPLEX 7.5.

5) When the result for the current connection is obtained from CPLEX, the information is used to update the existing network. The next connection request is accepted and the steps 1 - 5 are repeated for the new connection.

In order to show that this approach is feasible for practical-sized networks, we develop a C program and test it extensively on two well-known networks, NSFNET [20] and
ARPANET [2]. Our results indicate that the response time for our approach is more than adequate for these networks.

1.5. Thesis Organization

The remainder of this paper is organized as follow.

Chapter 2 presents literature review of WDM networks, and techniques for fault-tolerance in WDM networks. Chapter 3 describes the problem formulation, including the objective function, the constraints and thesis explanation. The concept is illustrated through a simple example. Chapter 4 explains the implementation of the experiments and shows the results. Chapter 5 concludes the formulation with a brief summary based on the implementation. Also, future work is recommended in this chapter.
Chapter 2. Literature Review

2.1. Introduction

In this chapter, we give a brief overview of some of the important concepts used in the remainder of this thesis. We discuss general WDM design techniques as well as design for fault tolerance. We also outline the basic concepts of linear programming.

2.2. Review of Survivable WDM Network

2.2.1. What is WDM?

WDM is a technology that puts data from different sources together on an optical fiber by dividing the high bandwidth of the fiber (up to 50 Tbits/s) [10] into a number of non-overlapping channels [21, 22]. Each channel operates asynchronously and in parallel at a different wavelength [23]. With current technology, theoretically up to 1000 separate channels of data can be multiplexed on a single optical fiber. This has been recently achieved in lab demonstrations at Lucent Technologies [24]. The current commercial technology is able to provide 128 channels at 2.5Gbps each, which means that up to 320 billion bits can be delivered in a second by the optical fiber [24]. WDM offers tremendous promise in providing high-capacity bandwidth, its traffic carrying capacity is significantly improved comparing with traditional synchronous optical network (SONET) [25]. The later one is a standard for optical telecommunications transport, which sets industry standards in the U.S. for telecommunications and other industries. Therefore, WDM (Wavelength Division Multiplexing) technology has become one of the most important candidates in building the current wide area network.
2.2.2. Design of WDM Networks

A lightpath in a WDM network is an end-to-end communication channel between a source and a destination. For such networks, the design problem is that of determining the route and channel number (or wavelength) for each lightpath (RWA problem).

The research of RWA problem involves two scenarios, static lightpath allocation scheme [26], and dynamic lightpath allocation scheme [19, 27, 28, 29]. Static allocation plans all the lightpaths in advance, and it can guarantee all of the paths will be assigned network resource to meet the requests. Dynamic allocation creates lightpaths on demand, and the lightpaths are taken down when the communication is over. Dynamic allocation cannot guarantee all the paths have enough resource to be allocated. The advantage is the network resource can be reused, which makes dynamic allocation more efficient.

2.2.3. Survivable WDM Networks

Survivable WDM networks have been addressed in many papers [2, 4, 23, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41].

There are two types of fault-management techniques [42, 43, 44]:

- Protection scheme [19, 23, 30, 31, 37, 40, 45, 46, 47, 48, 49]
- Restoration scheme [5, 50, 51, 52, 53]

In protection schemes, routes and channels for both primary and backup paths are reserved when the call is setup. In restoration schemes, the spare capacity available after the fault’s occurrence is utilized for rerouting the disrupted traffic.
Generally, the restoration scheme is more cost-efficient in resource allocation because it does not need to allocate resources for each backup path in advance. By reserving the backup path in advance, the protection scheme can save plenty of time for a network recovery when a failure is detected, and also provide guarantees on the recovery [10]. Meanwhile, the initial cost of protection scheme will be higher than the restoration scheme.

Protection-based schemes can be further sub-divided into (i) dedicated-path protection, and (ii) shared-path protection.

In shared-path protection, the path and wavelength used for a backup path can be shared with other existing backup paths (also called Backup Multiplexing) [54].

In dedicated-path protection, the wavelengths on the backup route are dedicated for one single backup path only, and cannot be shared with other backup paths.

Compared with dedicated-path protection, shared-path protection is more efficient and has been widely used in current networks. However, the recovery operation of shared-path protection can be complex and requires OXC reconfiguration in the intermediate nodes. Dedicated-path protection schemes are simpler and faster, and do not require reconfiguration of transit OXCs [55]. In this thesis, we use shared-path protection to achieve fault-tolerance. This is described in detail in section 2.2.3.1.

2.2.3.1. A Shared-Path Protection
In WDM networks, a lightpath is an end-to-end optical communication channel between the source and destination. If two lightpaths (P₁ & P₂) share the same fiber and transfer data at the same time, they must use different channels or wavelengths (λ₁ & λ₂) on the fiber in order to avoid interference.

There are two standard assumptions in many WDM networks. The first one is called single-fault assumption [10], which means that there is at most one fiber-fault in the physical network at any given time, when designing survivable optical networks. The second one is called the wavelength continuity constraint [6], which states that the same wavelength should be maintained along the entire lightpath. We will follow both assumptions in our thesis.

In the protection-based scheme, the primary path and its corresponding backup path are both reserved for each communication request [19]. If two primary paths P₁ & P₂ for two separate connections Cᵢ & Cⱼ are link-disjoint, then according to our single-fault assumption, their corresponding backup paths, Bᵢ & Bⱼ will never be used at the same time. Therefore, Bᵢ & Bⱼ can share the same fiber and be allocated same wavelength on the shared fiber. An example illustrating shared-path protection is given in Figure 2.1.

![Figure 2.1. A Sample of Shared-Path Protection](image-url)
In the above physical network, there are five nodes (0, 1, 2, 3, 4), and seven bi-directional edges (0-1, 1-2, 2-3, 3-4, 0-4, 0-3, 1-3). A connection $C_1$ has primary path $P_1$, using the route $0 \rightarrow 1$ and wavelength $\lambda_1$. The edge-disjoint backup path $B_1$ uses the route $0 \rightarrow 3 \rightarrow 1$ and wavelength $\lambda_1$. A new connection $C_2$ from node 4 to node 2 is now required. Let the primary path $P_2$ use route $4 \rightarrow 3 \rightarrow 2$, and its edge-disjoint backup path $B_2$ use the route $4 \rightarrow 0 \rightarrow 3 \rightarrow 1 \rightarrow 2$. So, $P_1$ and $P_2$ are fiber-disjoint. Based on the single-fault assumption, backup paths $B_1$ and $B_2$ will never be employed at the same moment. Hence, backup paths $B_1$ and $B_2$ could be allocated the same wavelength, $\lambda_1$, even though they share the link $0 \rightarrow 3$.

Let's consider another new connection $C_3$ required from node 0 to node 2. The route of the primary path $P_3$ could be $0 \rightarrow 1 \rightarrow 2$, or $0 \rightarrow 3 \rightarrow 2$. If we take $0 \rightarrow 1 \rightarrow 2$, its edge-disjoint backup path, $B_3$, could be $0 \rightarrow 3 \rightarrow 2$. Since $P_1$ and $P_3$ are not fiber disjoint (both use edge $0 \rightarrow 1$), and the corresponding backup paths $B_1$ and $B_3$ share a common edge $0 \rightarrow 3$, we can see that $P_1$ and $P_3$ must be allocated different wavelength ($\lambda_1$ and $\lambda_2$ respectively).

2.3. MILP and CPLEX

To implement the shared path protection scheme based on QoS in WDM networks, an efficient mixed-integer linear programming (MILP) formulation is developed in this paper to find the best resource allocation for primary paths and backup paths (if necessary).
In the following section, we give a brief overview of the MILP. We have used CPLEX [56], a well-known tool for linear optimization, for obtaining the solutions to our MILP.

2.3.1. What is MILP?

MILP is the abbreviation of Mixed-Integer Linear Programming. To study MILP, we first need to understand Linear Programming (LP).

I. What is Linear Programming (LP)?

Linear Programming (LP) is a most important and most widely used optimization technique designed to optimize the usage of limited resources in operation research (OR). Linear Programming problems are characterized by objective functions and constraints. "The key to LP is constraints; by modeling real-life limitations as rigid mathematical equations, best values for unknowns can be determined accurately, efficiently and mechanically." [57]. LP is the basis for the development of solution algorithms of operation research (OR) models.

The LP framework is given below [58]:

**Objective Function:**

Maximize (or Minimize)

\[ z = c_1x_1 + \ldots + c_nx_n \]

**Constraints:**

Subject to:

\[ a_{11}x_1 + \ldots + a_{1n}x_n \leq b_1 \]
\[ a_{21}x_1 + \ldots + a_{2n}x_n \leq b_2 \]
\[
\ldots \ldots
\]
\[ a_{m1}x_1 + \ldots + a_{mn}x_n \leq b_m \]

Bounds: \( x_1, x_2, \ldots, x_n \geq 0 \)

Here is a sample of Linear Programming problem:

**Objective Function:**

Maximize \( z = 3x_1 + 2x_2 \)

**Constraints:**

Subject to:

1. \( x_1 + 2x_2 \leq 6 \)
2. \( 2x_1 + x_2 \leq 8 \)
3. \( -x_1 + x_2 \leq 1 \)
4. \( x_2 \leq 2 \)
5. \( x_2 \geq 0 \)
6. \( x_1 \geq 0 \)

Figure 2.2 shows the graphic solution of the above problem. Constraints 1 to 6 have been displayed in this graph. These six constraints compose the shadowed solution area. Every dot in this shadowed area meets with the request of the six constraints. The dotted line is one of the expressions of the objective function, when it passes the point L, objective \( z = 3x_1 + 2x_2 \) has the maximum value.
II. ILP and MILP

Integer Linear Programming is Linear Programming with the additional constraints, in which some or all of the variables must be integer variables. If all the variables are integers, it is known as Pure Integer Linear Programming (PILP).

If some of the variables are integer, and the others are continuous variables, then it is known as Mixed-Integer Linear Programming (MILP).

In this research, we try to solve a network optimization program, and the involved variables consist of both integer and continuous variables. Therefore, we will implement the MILP problem to simulate the particular network and solve the network optimization problem.

MILP Framework:

**Objective Function:**
Maximize: (or Minimize)
\[ z = c_1x_1 + \ldots + c_nx_n \]

**Constraints:**

Subject to: 
- \[ a_{11}x_1 + \ldots + a_{1n}x_n \leq b_1 \]
- \[ a_{21}x_1 + \ldots + a_{2n}x_n \leq b_2 \]
- \[ \ldots \]
- \[ a_{m1}x_1 + \ldots + a_{mn}x_n \leq b_m \]

**Bounds:** 
\[ x_1, \ldots, x_n \geq 0 \]

\[ x_i \text{ is integer or } x_i \text{ is continuous variables } (i \leq n) \]

In our simulations, we use CPLEX [56], a well-known tool for solving linear, mixed-integer and quadratic programming problems.
Chapter 3. Problem Formulation

3.1. Introduction

In this chapter, we describe our MILP formulation for dynamic lightpath allocation in WDM networks, using a protection-based scheme. A novel aspect of our formulation is that we consider the quality of service (QoS) required for a connection, when allocating resources. We divide the quality of service into three levels, each requiring a different amount of resources.

The objective of our formulation is not only to route along the shortest path with valid wavelengths, but also to allocate the wavelengths and routes with various levels of QoS efficiently. This concept will reduce the amount of idle network resources in the network, and also provide quality of service at different levels based on various requests.

3.2. Quality of Service (QoS)

We defined three different levels of services for the shared-path protection WDM network. The first level (level-2) has the highest priority, and each primary path at this level has a pre-assigned backup path available at anytime. The second level (level-1) has no pre-assigned backup path. However, it has a dedicated primary path that cannot be preempted by any higher-level connection. The third level (level-0) has the lowest priority. It has no pre-assigned backup path and its primary path may be shared with the backup path of a higher priority path.
The three levels of service are described below in detail.

Level 0: This is the lowest level of service. No backup path is provided for level-0 connection. Furthermore, the channels used by the primary paths for these connections may be allocated to the backup paths of higher-level connections (i.e. level-2 backup paths). This means that these connections can be preempted if the corresponding backup paths need to be employed, due to any network fault.

Level 1: This is the second level of service. No backup path is created when the connection is setup. Their primary paths do not share any resources with higher-level paths, and hence they cannot be preempted.

Level 2: This is the highest level of service. A primary path and an edge-disjoint backup path are both created during call setup.

For level-0 and level-1 connections, restoration techniques may still be used to get a new path after a fault has been detected. This method of recovery typically leads to a larger delay. We are not concerned with the restoration techniques in this thesis.

3.3. Physical Network Constraints

In this section, we outline the main constraints needed for designing a survivable WDM networks.
1) The Primary path and its backup path (if necessary) must be fiber-disjoint. Within our formulation, only level-2 requests have backup paths. For a level-2 connection, when there is no fault in the network, only the primary paths are activated. If a network fault is detected in any primary path, its corresponding backup path will be activated. Therefore, the primary path and its backup path must be fiber-disjoint to ensure that they are both not affected by a single network fault at the same time. For level-0 and level-1 requests, this constraint is unnecessary since no backup path is setup.

2) Both primary path and backup path (if necessary) must have exactly one wavelength associated with it. This means a primary or backup path must be allocated the same channel on each physical edge along its route. This is based on the wavelength continuity constraint [6]. In WDM networks, the available fiber bandwidth is divided into WDM channels. A device called wavelength converter allows the optical signal on a wavelength to be converted into another wavelength. Although the wavelength converters can improve network-blocking performance, the high cost of wavelength converters means that they are typically not cost-effective [59]. We do not use wavelength converters and therefore enforce the wavelength continuity constraint in our formulation.

3) A new primary path must be channel-disjoint with all other existing primary paths. That is because, for all the three levels of requests, primary paths cannot share the same channel under any situation.
4) A new primary path (level-1 or level-2) must be channel-disjoint with all other existing backup paths. According to our definition of the three levels of QoS, only the primary paths of level-0 can share the same channel with the backup paths of level-2. Neither level-1 nor level-2 primary paths can share the same channel with any existing backup paths.

5) A new backup path (level-2) must be channel-disjoint with all other existing primary paths of level-1 or level-2. According to our definition of the three levels of QoS, new backup paths (only applicable for level-2 request) can only share the same channels with level-0 primary paths, it prohibits the situation that a new backup path (level-2) is assigned the same channel with an existing level-1 or level-2 primary path.

6) If backup multiplexing is allowed, then the new backup path may share a channel with an existing backup path if and only if the corresponding primary paths are edge-disjoint. According to our single-fault assumption, two edge-disjoint primary paths cannot be disrupted at the same time. Hence, only one backup path will be activated to recover the corresponding damaged primary path at any given time. Therefore, multiple backup paths can share the same channel as long as their corresponding primary paths are edge-disjoint.

In the following sections, we explore how to convert the physical network topology constraints into the mathematic formulations.
3.4. MILP Formulation

3.4.1. Notations

We use the following notations for our MILP formulation:

- $E$ is the set of edges in the physical network, $|E| = m$;

- $N$ is the set of nodes in the physical network, $|N| = n$;

- $K$ is the set of channels that each edge $(i, j) \in E$ can accommodate (with $|K| = K$);

- $P^1$ is a list of primary paths already established, where $P_p^1$ is the $p^{th}$ primary path;

- $P^2$ is a list of backup paths already established, where $P_p^2$ is the $p^{th}$ backup path;

- $a_{ij}^p$ is the primary edge-path incidence matrix, with

$$a_{ij}^p = \begin{cases} 
1, & \text{if edge } (i, j) \text{ is in the } p^{th} \text{ primary path} \\
0, & \text{otherwise}
\end{cases}$$

- $b_{ij}^p$ is the corresponding backup edge-path incidence matrix, with

$$b_{ij}^p = \begin{cases} 
1, & \text{if edge } (i, j) \text{ is in the } p^{th} \text{ backup path} \\
0, & \text{otherwise}
\end{cases}$$

- $k_1^p (k_2^p)$ is the channel assigned to the $p^{th}$ primary (backup) path, for all $p$, $1 \leq p \leq P$;

- $Q^p = \{0, 1 \text{ or } 2\}$, indicates the level of service for the $p^{th}$ existing path;

- $Q_{new} = \{0, 1 \text{ or } 2\}$, indicates the level of service for the new required path;
We also design the following variables:

- For each existing backup path $p$, $p \in P^2$, a non-negative continuous variable $\delta_p$, $0 \leq \delta_p \leq 1$. $\delta_p$ is a continuous variable. $\delta_p$ has a value 1 if and only if the new backup path shares an edge and channel with the $p^{th}$ existing backup path. Otherwise, $\delta_p$ has a value 0.

- For each $(i, j) \in E$, a binary variable $x_{ij}$

$$x_{ij} = \begin{cases} 
1, & \text{if the new primary path uses edge } (i, j) \\
0, & \text{otherwise}
\end{cases}$$

- For each $(i, j) \in E$, a binary variable $y_{ij}$

$$y_{ij} = \begin{cases} 
1, & \text{if the new backup path uses edge } (i, j) \\
0, & \text{otherwise}
\end{cases}$$

If $Q_{\text{new}} = 0$ or 1, then no backup path is needed and $y_{ij} = 0$, $\forall (i, j) \in E$.

- For all $k$, $1 \leq k \leq K$, a binary variable $W_k$ ($Z_k$)

$$W_k = \begin{cases} 
1, & \text{if the new primary path is allocated channel } k \\
0, & \text{otherwise}
\end{cases}$$

and

$$Z_k = \begin{cases} 
1, & \text{if the new backup path is allocated channel } k \\
0, & \text{otherwise}
\end{cases}$$

If $Q_{\text{new}} = 0$ or 1, then $Z_k = 0$ for all $k$, $1 \leq k \leq K$, because there is no backup path needed.
• For each \((i, j) \in E\), a non-negative continuous variable \(c_{ij}\), \(0 \leq c_{ij} \leq 1\) and a binary variable \(m_{ij}\), \(m_{ij}\) indicates whether the wavelength used by the new backup path is also being used on link \((i, j)\) by another backup path. Based on the value of \(m_{ij}\), \(c_{ij}\) indicates (for level 2 lightpaths only) whether the new backup path uses any additional resource on link \((i, j)\) or not. If the current backup path is multiplexed with an existing backup path on link \((i, j)\), then \(c_{ij} = 1\). This indicates that no new resources need to be allocated for the backup path on that link \((i, j)\). Otherwise, \(c_{ij} = 0\).

3.4.2. Equations of the MILP Formulation

The following contents are the mathematical equations of the MILP formulation, which consists of two parts:

I. Objective Function

II. Constraints

These mathematical equations will be converted into CPLEX LP format, which is executable by ILOG CPLEX in the experiment.

Objective function:

\[
\text{Minimize} \quad \sum_{(i,j) \in E} x_{ij} + \sum_{(i,j) \in E} (y_{ij} - c_{ij}) \tag{3.1}
\]

Constraints:
- Flow conservation for the primary path:
  \[ \sum \limits_{j} x_{ij} - \sum \limits_{j} x_{ji} = \begin{cases} 
  1, & \text{if } i = s \text{ (source node)} \\
  -1, & \text{if } i = d \text{ (destination node)} \\
  0, & \text{otherwise} 
\end{cases} \quad \forall i \quad (3.2) \]

- Flow conservation for the backup path:
  \[ \sum \limits_{j} y_{ij} - \sum \limits_{j} y_{ji} = \begin{cases} 
  1, & \text{if } i = s \text{ (source node)} \\
  -1, & \text{if } i = d \text{ (destination node)} \\
  0, & \text{otherwise} 
\end{cases} \quad \forall i, \text{ for } Q_{\text{new}} = 2 \quad (3.3a) \]

  \[ y_{ij} = 0, \ \forall (i, j) \in E \text{ for } Q_{\text{new}} = 0 \text{ or } 1 \quad (3.3b) \]

- The primary path must be link disjoint with respect to the backup path:
  \[ x_{ij} + y_{ij} \leq 1 \quad \forall (i, j) \in E \quad (3.4) \]

- The primary path must have exactly one wavelength associated with it, i.e. it must be allocated the same channel number on each edge in the path. This enforces the wavelength continuity constraint.
  \[ \sum \limits_{k=1}^{K} W_k = 1 \quad (3.5) \]

- If a backup path is to be created (i.e. if the new request is a level 2 request), it must have exactly one wavelength associated with it. For level 0 and level 1 requests, there should be no channels allocated to a backup path.
  \[ \sum \limits_{k=1}^{K} Z_k = 1 \quad \text{for } Q_{\text{new}} = 2 \quad (3.6a) \]
\[ \sum_{k=1}^{K} Z_k = 0 \quad \text{for } Q_{\text{new}} = 0 \text{ or } 1 \quad (3.6b) \]

- The new primary path must be channel-disjoint with all other existing primary paths.
\[ x_{ij} + W_k^i \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, \quad p = 1, 2, \ldots, P \quad (3.7a) \]

- If the new primary path has service level 1 or 2, then it must be channel-disjoint with all other existing backup paths. This restriction is not enforced for level 0 primary paths, which may be preempted if a higher-level backup path multiplexed with it needs to be activated.
\[ x_{ij} + W_k^i \leq 1, \quad \forall (i, j) \ni b_{ij}^p = 1, \text{ for } Q_{\text{new}} = 1 \text{ or } 2, \text{ and } p = 1, 2, \ldots, P \quad (3.7b) \]

- A new backup path must be channel-disjoint with all other existing primary paths of level 1 or level 2. Equation 3.8 is only used if \( Q_{\text{new}} = 2 \). If \( Q_{\text{new}} = 0 \) or 1, then equation 3.8 is always satisfied, based on equations (3.3b) and (3.6b). So equation 3.8 is redundant.
\[ y_{ij} + Z_k^i \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, \text{ for } Q^p = 1 \text{ or } 2, \text{ and } Q_{\text{new}} = 2, \text{ and } p = 1, 2, \ldots, P \quad (3.8) \]

- If backup multiplexing is allowed then the new backup path may share a channel on link \((i, j)\) with the \(p\)th backup path only if the corresponding primary paths are edge disjoint. Equations (3.9a) – (3.9d) enforce the constraints for backup multiplexing.
\[ Z_k^2 + y_{ij} - \delta_p \leq 1, \quad \forall (i, j) \ni b_{ij}^p = 1, \quad p = 1, 2, \ldots, P \quad (3.9a) \]
\[ \delta_p - Zk_p^p \leq 0, \quad p = 1, 2, \ldots, P \]  \hspace{1cm} (3.9b)

\[ \delta_p - \sum y_{ij} \leq 0, \quad \forall (i, j) \ni b_{ij}^p = 1 \quad p = 1, 2, \ldots, P \]  \hspace{1cm} (3.9c)

\[ x_{ij} + \delta_p \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, p = 1, 2, \ldots, P \]  \hspace{1cm} (3.9d)

- The following set of equations include whether backup multiplexing has occurred on a particular link \((i, j)\) in the new backup path.

\[ m_{ij} - \sum_{p \ni b_{ij}^p = 1} Zk_p^p \leq 0, \quad \forall (i, j) \in E \]  \hspace{1cm} (3.10a)

\[ p \cdot m_{ij} \geq \sum_{p \ni b_{ij}^p = 1} Zk_p^p, \quad \forall (i, j) \in E \]  \hspace{1cm} (3.10b)

\[ y_{ij} + m_{ij} - c_{ij} \leq 1, \quad \forall (i, j) \in E \]  \hspace{1cm} (3.10c)

\[ y_{ij} - c_{ij} \geq 0, \quad \forall (i, j) \in E \]  \hspace{1cm} (3.10d)

\[ m_{ij} - c_{ij} \geq 0, \quad \forall (i, j) \in E \]  \hspace{1cm} (3.10e)

3.4.3. Explanation of the Equations

In this section, we provide the detailed explanations for the above equations.

Equation (3.1):

Minimize \[ \sum_{(i,j) \in E} x_{ij} + \sum_{(i,j) \in E} (y_{ij} - c_{ij}) \]

Equation (3.1) is the objective function of the formulation. We try to minimize the amount of optical resources used in establishing a new call.

\[ \sum_{(i,j) \in E} x_{ij} \] shows that each edge in the primary path needs one channel, which is the network resource we need to minimize.
If there is no backup multiplexing, each edge in the backup path needs one channel. In this case, the number of channels used can be minimized by simply minimizing the sum of the lengths of the primary and backup paths. In this case, the expression $c_{ij} = 0$ and the objective function is:

$$\text{Min} \left( \sum_{(ij) \in E} x_{ij} + \sum_{(ij) \in E} y_{ij} \right)$$

If there is backup multiplexing, when the new backup path uses the same channel on link $(i, j)$ and sharing with an existing backup path, then no new resource is needed on the link $(i, j)$ for the new backup path, and expression $c_{ij} = 1$. So the second term is $\sum_{(ij) \in E} (y_{ij} - c_{ij})$.

For links which are not in the new backup path, $c_{ij}$ is automatically set to 0 (by equation 3.10d).

Equation (3.2):

$$\sum_{j} x_{ij} - \sum_{j} x_{ji} = \begin{cases} 
1, & \text{if } i = s \text{ (source node)} \\
-1, & \text{if } i = d \text{ (destination node)} \\
0, & \text{otherwise} \end{cases} \quad \forall i$$

Equation (3.2) is the standard flow conservation equation [60] to define the primary path from a source to a destination.

In a primary path, for any node $i$, when $i$ is the source node, for any of the edge $(i, j) \in E$, there must be one and only one primary edge link $x_{ij} = 1$. 

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Meanwhile, for any edge path \((i, j) \in E\), \(x_{ji} = 0\). Hence, \(\sum_j x_{ij} - \sum_j x_{ji} = 1\).

When \(i\) is the destination node, for any edge path \((i, j) \in E\), there must be one and only one primary edge link \(x_{ji} = 1\). Meanwhile, for any edge path \((i, j) \in E\), \(x_{ij} = 0\). Hence, \(\sum_j x_{ij} - \sum_j x_{ji} = -1\).

If node \(i\) belongs to the primary path, but neither the source node nor destination node, then \(\sum_j x_{ij} = 1\) and \(\sum_j x_{ji} = 1\).

If node \(i\) is not in the primary path, then \(\sum_j x_{ij} = 0\) and \(\sum_j x_{ji} = 0\).

In both cases, we have \(\sum_j x_{ij} - \sum_j x_{ji} = 0\).

Equation (3.3a):

\[
\sum_j y_{ij} - \sum_j y_{ji} = \begin{cases} 
1, & \text{if } i = s \text{ (source node)} \\
-1, & \text{if } i = d \text{ (destination node)} \\
0, & \text{otherwise}
\end{cases} \quad \forall i, \text{ for } Q_{\text{new}} = 2
\]

Equation (3.3a) is the standard flow conservation equation [60] to define the backup path from a source to a destination.

When \(Q_{\text{new}} = 2\), the backup path is necessary. For any node \(i\) in the backup path, when \(i\) is the source node, for any edge path \((i, j) \in E\), there is one and only one
backup edge link $y_{ij} = 1$. Meanwhile, for any edge path $(i, j) \in E$, $y_{ji} = 0$. Hence,
\[ \sum_j y_{ij} - \sum_j y_{ji} = 1. \]

When $i$ is the destination node, for any edge path $(i, j) \in E$, there must be one and only one backup edge link $y_{ji} = 1$. Meanwhile, for any of the edge path $(i, j) \in E$, $y_{ij} = 0$. Hence, $\sum_j y_{ij} - \sum_j y_{ji} = -1$.

If node $i$ belongs to the backup path, but neither the source node nor destination node, then $\sum_j y_{ij} = 1$ and $\sum_j y_{ji} = 1$.

If node $i$ is not in the primary path, then $\sum_j y_{ij} = 0$ and $\sum_j y_{ji} = 0$.

In both cases, we have $\sum_j y_{ij} - \sum_j y_{ji} = 0$.

Equation (3.3b):
\[ y_{ij} = 0, \quad \forall (i, j) \in E \text{ for } Q_{new} = 0 \text{ or } 1 \]

Equation (3.3b) states that no backup path is created for level 0 and level 1 lightpaths.

Equation (3.4):
\[ x_{ij} + y_{ij} \leq 1 \quad \forall (i, j) \in E \]
Equation (3.4) shows that a primary path must be edge-disjoint with the corresponding backup path. Therefore, primary path $x_{ij}$ and its backup path $y_{ij}$ cannot both be 1 for a given edge $(i, j)$ at the same time.

Equation (3.5):

$$
\sum_{k=1}^{K} W_k = 1
$$

Equation (3.5) ensures that only one channel number is reserved for the new primary path.

Equation (3.6a):

$$
\sum_{k=1}^{K} Z_k = 1 \quad \text{for } Q_{\text{new}} = 2
$$

Equation (3.6a) ensures that only one channel number is reserved for new backup lightpath of level 2 services.

Equation (3.6b):

$$
\sum_{k=1}^{K} Z_k = 0 \quad \text{for } Q_{\text{new}} = 0 \text{ or } 1
$$

Equation (3.6b) ensures that no channel number is needed for new backup lightpath of level 0 or 1 services.
Equation (3.7a):

\[ x_{ij} + W_{k_i^p} \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, \quad p = 1, 2, \ldots, P \]

In equation (3.7a), \( \forall (i, j) \ni a_{ij}^p = 1 \), the edge \((i, j)\) is in the \( p^{th} \) existing primary path. This existing \( p^{th} \) primary path has already been allocated wavelength \( k_i^p \). \( x_{ij} = 1 \) means the new primary path uses edge \((i, j)\). \( W_{k_i^p} = 1 \) means the new primary path is assigned the same wavelength number as the existing \( p^{th} \) primary path. As we know, if the new primary path shares the same wavelength with an existing primary path, it cannot share any same edge. So when \( W_{k_i^p} = 1 \), \( x_{ij} \) cannot equal to 1. Or, if the new primary path shares a same edge \((i, j)\) with an existing primary path, they cannot share a same wavelength. So when \( x_{ij} = 1 \), \( W_{k_i^p} \) cannot be 1. Therefore, equation (3.7a) prohibits the situation where the new primary path is assigned the same wavelength number as the \( p^{th} \) primary path and shares the same fiber.

Equation (3.7b):

\[ x_{ij} + W_{k_j^p} \leq 1, \quad \forall (i, j) \ni b_{ij}^p = 1, \quad Q_{new} = 1 \text{ or } 2, \quad p = 1, 2, \ldots, P \]

Equation (3.7b) works in exactly the same way as equation (3.7a), if \( \forall (i, j) \ni b_{ij}^p = 1 \), the edge \((i, j)\) is in the \( p^{th} \) existing backup path. This existing \( p^{th} \) backup path has already been allocated wavelength \( k_j^p \). \( x_{ij} = 1 \) means the new primary path uses edge \((i, j)\). \( W_{k_j^p} = 1 \) means the new primary path is assigned the same wavelength number as the existing \( p^{th} \) backup path. As we know, if the new
primary path shares the same wavelength with an existing backup path, it cannot share any same edge. So when $W_{k_2}^p = 1, x_{ij}$ cannot be equal to 1. Or, if the new primary path shares a same edge (i, j) with an existing backup path, it cannot share a same wavelength. So, when $x_{ij} = 1$, $W_{k_2}^p$ cannot be 1. Therefore, equation (3.7b) prohibits the situation where the new primary path is assigned the same wavelength number as the $p^{th}$ backup path and shares a common fiber. This situation is suitable for a new request with $Q_{new} = 1$ or 2. When $Q_{new} = 0$, this new required primary path is allowed to share the wavelength with an idle backup path.

Equation (3.8):

$$y_{ij} + Z_{k_1}^p \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, Q^p = 1 \text{ or } 2, Q_{new} = 2, p = 1, 2, \ldots, P$$

Equation (3.8) is similar to equation (3.7a) and (3.7b), if $\forall (i, j) \ni a_{ij}^p = 1$, the edge (i, j) is in the $p^{th}$ existing primary path of level 1 or level 2. The existing $p^{th}$ primary path has already been allocated wavelength $k_1^p$. $y_{ij} = 1$ meaning the new backup path uses edge (i, j). $Z_{k_1}^p = 1$ means the new backup path is assigned the same wavelength number as the existing $p^{th}$ primary path. As we know, if the new backup path shares the same wavelength with an existing primary path, it cannot share any same edge. So, when $Z_{k_1}^p = 1$, $y_{ij}$ cannot equal to 1. Or, if the new backup path shares a same edge (i, j) with an existing primary path, it cannot share a same wavelength. So when $y_{ij} = 1$, $Z_{k_1}^p$ cannot be 1. Therefore, equation (3.8) prohibits the situation where the new backup path is assigned the same
wavelength number as the pth primary path of level 1 or level 2, and shares the same fiber. Equation (3.8) is only used for new request with Q_{new} = 2. Because only request with Q_{new} = 2 will need the backup path. For a request with Q_{new} = 0 or 1, no backup path is needed (y_{ij} = 0, \forall (i, j)), and equation (3.8) is always satisfied based on equation (3.3b) and (3.6b). However, the new backup path can share a link and a wavelength with an existing level 0 primary path, since the backup path of level 2 can preempt the level 0 connection.

Equation (3.9a) – (3.9d):

\[
Z_{k2}^p + y_{ij} - \delta_p \leq 1, \quad \forall (i, j) \ni b_{ij}^p = 1, p = 1, 2, ..., P \quad (3.9a)
\]

\[
\delta_p - Z_{k2}^p \leq 0, \quad p = 1, 2, ..., P \quad (3.9b)
\]

\[
\delta_p - \sum_{i,j} y_{ij} \leq 0, \quad \forall (i, j) \ni b_{ij}^p = 1 \quad (3.9c)
\]

\[
x_{ij} + \delta_p \leq 1, \quad \forall (i, j) \ni a_{ij}^p = 1, p = 1, 2, ..., P \quad (3.9d)
\]

Equations (3.9a) to (3.9d) together implement the constraints for multiplexing the backup path of a new level-2 request with an existing backup path (Q^p = 2).

When \( \delta_p = 1 \):

From equation (3.9b), we have \( Z_{k2}^p \geq 1 \), so \( Z_{k2}^p = 1 \) (because \( Z_{k2}^p \) is a binary variable). This means the \( p \)th backup path shares the same channel number with the new backup path. According to (3.9a), we have \( y_{ij} \leq 1, (\forall (i, j) \ni b_{ij}^p = 1) \). And, according to (3.9c), we have \( \sum y_{ij} \geq 1, (\forall (i, j) \ni b_{ij}^p = 1) \). So, when \( \forall (i, j) \ni b_{ij}^p \)
= 1, \( y_{ij} = 1 \). Which means the \( p \)th backup path shares the same edge \((i, j)\) with the new backup path.

When the new backup path shares the same edge \((i, j)\) and the same channel number with the \( p \)th backup path, according to (3.9d), we see that \( x_{ij} \leq 0 \), which means no edge \((i, j) \in p \)th primary path can belong to the new primary path.

When \( \delta_p = 0 \):

If the \( p \)th backup path does not use the same wavelength as the new backup path to be built, then equation (3.9b) is \( Zk^p_{2} = 0 \), which indicates that \( \delta_p = 0 \).

Under the same situation, if the new backup path does not share any edge with the \( p \)th backup path, which means \( \sum y_{ij} = 0 \), from equation (3.9c), we have \( \delta_p = 0 \).

When \( \delta_p = 0 \) and \( Zk^p_{2} = 0 \), (3.9a) and (3.9d) are always satisfied and becomes redundant.

Equation (3.10a) – (3.10e):

\[
\begin{align*}
m_{ij} - \sum_{p \in \mathcal{E}} Zk^p_{2} &\leq 0, \\
p \neq b^p_{ij} &\neq 1 \\
\forall (i, j) &\in \mathcal{E} \\
\tag{3.10a} \\
p \cdot m_{ij} &\geq \sum_{p \in \mathcal{E}} Zk^p_{2}, \\
p \neq b^p_{ij} &\neq 1 \\
\forall (i, j) &\in \mathcal{E} \\
\tag{3.10b} \\
y_{ij} + m_{ij} - c_{ij} &\leq 1, \\
\forall (i, j) &\in \mathcal{E} \\
\tag{3.10c} \\
y_{ij} - c_{ij} &\geq 0, \\
\forall (i, j) &\in \mathcal{E} \\
\tag{3.10d} \\
m_{ij} - c_{ij} &\geq 0, \\
\forall (i, j) &\in \mathcal{E} \\
\tag{3.10e}
\end{align*}
\]
Equations (3.10a) to (3.10e) are used to determine whether the backup path for a new request uses a channel on link \((i, j)\) that has already been allocated to an existing backup path, i.e., whether or not backup multiplexing will take place on link \((i, j)\).

If so, then \(c_{ij} = 1\), and the cost of link \((i, j)\) in the backup path can be excluded from the objective function.

Equations (3.10a) and (3.10b) define the binary variable \(m_{ij}\). When \(m_{ij} = 1\), it means there is at least one existing backup path which traverses link \((i, j)\) and uses the same wavelength as the new backup path \((Zk_2^p = 1)\). Even if a link \((i, j)\) is not on the new backup path, i.e. \(y_{ij} = 0\), from (3.10c), \(m_{ij}\) may still have the value of 1.

When \(m_{ij} = 0\), it means no existing backup path is multiplexing with the new backup path; or \(y_{ij} = 0\), which means link \((i, j)\) is not on the new backup path. From equation (3.10d) or (3.10e), we have \(c_{ij} = 0\).

If both \(m_{ij} = 1\) and \(y_{ij} = 1\), from equation (3.10c), we have \(c_{ij} = 1\).

3.4.4. Complexity of the Formulation

Assuming there are \(n\) nodes in the physical topology, and no path has more than \((n-1)\) edges, the number of constraints with the MILP formulation is bounded by:

\[2n + 6|E| + 2P + 5(n-1)P + 2.\]
3.5. A Simple Example

In this section, we illustrate our dynamic lightpath allocation strategy through a simple example. We consider a network with five nodes and seven bi-directional edges (Figure 3.1). The network has three existing connections (C₂, C₁, and C₀):

C₂: A level-2 connection from source 4 to destination 2 has a primary path P₂ (4 → 2), and a link-disjoint backup path B₂ (4 → 0 → 1 → 2). Both the primary and backup paths are allocated wavelength λ₁.

C₁: A level-1 connection from source 0 to destination 3 has a primary path, P₁, (0 → 3) only, which also can be assigned wavelength λ₁ since it is link-disjoint with P₂ and B₂, also level-1’s primary path, P₁, cannot not be shared by level-2’s backup paths.

C₀: A level-0 connection from source 0 to destination 1 has a primary path P₀ (0 → 1) only. It also can share the same channel with level-2’s backup path B₂. This means level-0’s primary path, P₀, can use wavelength λ₁ which is also allocated to B₂. When level-2’s primary path, P₂, has a failure, the traffic is switched to backup path, B₂. Under such a situation, level-0 path, P₀, will be disabled.

Figure 3.1. A simple WDM dynamic lightpath allocation example 1
We have a new level-2 request from source node 0 to destination node 2 now. Its primary path, $P_3$, passes through route $0 \rightarrow 1 \rightarrow 2$, and the edge-disjoint backup path, $B_3$, passes through route $0 \rightarrow 3 \rightarrow 2$ (See Figure 3.2). Because the new primary path $P_3$ is sharing the edge $0 \rightarrow 3$ with $P_1$, and sharing the edge $3 \rightarrow 2$ with $P_2$, we have to assign a different wavelength $\lambda_2$ to the new primary path $P_3$. For its new backup path $B_3$, it is allowed to share a common channel with level-0 primary path $P_0$. However, since their primary paths $P_2$ and $P_3$ are not edge-disjoint (sharing edge $3 \rightarrow 2$), the corresponding backup paths $B_2$ and $B_3$ cannot use backup multiplexing, which means we also have to assign a different wavelength $\lambda_2$ to the new backup path $B_3$.

![Figure 3.2. A simple WDM dynamic lightpath allocation example 2](image-url)
Chapter 4. Experiments and Results

4.1. Simulation Strategy

In this chapter, we describe our program to simulate the dynamic mixed-integer linear programming (MILP) formulation. This program accepts an input file providing all the un-changeable network parameters, including the set of nodes, set of physical edges, and available channel numbers. The simulation process is outlined below.

I. The system reads in all the parameters from the input file, to initialize the network topology.

II. The system randomly generates the following variables for the first Connection C₀:
   - The quality of service level of Connection C₀;
   - The source node;
   - The destination node (different from the source node created earlier).

III. The above information is used to generate the mathematic constraints (described in section 3.4.2). The mathematic constraints are then converted into a MILP problem in LP format.

IV. CPLEX is used to solve the MILP and obtain an optimized configuration for creating a new connection. This includes the route for primary path and the backup path (if necessary), as well as the channel assigned to the primary path and backup path (if necessary).
V. After obtaining the route(s) and assigned channel(s) for the new connection, the program records these values into the current network and upgrades the network topology. The updated logical topology contents are saved into the network as existing variables for the next network connection request.

VI. This completes one cycle in the simulation process. The system then randomly generates the set of variables for the next connection $C_1$, and all the above steps are re-run for $C_1$.

VII. The process is terminated if the maximum number of connections is achieved, or there are two connection failures.

4.2. Flowchart

This MILP program includes five different modules:

I. Network topology initialization

II. Run “in_to_out” function, to generate the LP format from the MILP equations

III. Run the MILP in CPLEX 7.5 and get the objective value and other results

IV. Display & record output, and update the existing network topology

V. Run multiple-request dynamically

Following is the flowchart showing the major modules in the MILP program (Figure 4.1).
Start

Initialize network topology;
connection_number = 0;
failure_time = 0;
Create QoS, Source node and Destination node for Connection 0.

Run in_to_out() function and get the LP format for MILP

Run MILP in CPLEX, and get the objective value & other results

Display the Output; Record the Output

connection_number++;
Re-generate: QoS, source node, destination node for new connection;

If maximum no. of successful connections has been achieved?
AND
if failure time >= 2?

No

Yes

End

Figure 4.1. Flowchart of MILP problem solution
4.3. Experiments and Results

We use CPLEX 7.5 [56] to solve the MILP formulation. The experiments were run on a Sun Solaris 5.8 system with 64-bits, 333-MHz processor and 256-MB RAM. We run the experiments on two standard well-known networks: NSFNET [20] (shown in Figure 4.2) and ARPANET [2] (shown in Figure 4.3). NSFNET is the abbreviation of National Science Foundation Network, which has 14 nodes and 21 links. NSFNET was a network for computing research deployed in the mid-1980s. Then, it became the first backbone infrastructure for the commercial public Internet (see Figure 4.2).

![Figure 4.2. The 14-node 21-link NSFNET](image)

ARPANET was the network that became the basis for the Internet, funded mainly by U.S. military in 1980s. It was replaced over time in the 1980's by a separate new military network, the Defense Data Network, and NSFNET (see Figure 4.3).

![Figure 4.3. The 20-node 31-link ARPANET](image)
In all the experiments, the MILP program will be run to accept multiple service requests. The quality of service, source and destination node for each connection will be created randomly. In each experiment, when we have two failures, the testing program is terminated. Failures occur when there is not enough available network resource (i.e. channels) to be assigned to the randomly generated request. From the repetitive experiments, we notice that after failures happen twice in each test, the chance for successful connections decreases rapidly. That is the reason we select 2 as the maximum number of failures to terminate each experiment.

We also will run the experiments with different network parameters values:

- First, QoS rate:

  Case 1:  Level-2 rate = 20%  Level-1 rate = 40%  Level-0 rate = 40%
  Case 2:  Level-2 rate = 60%  Level-1 rate = 20%  Level-0 rate = 20%

- Second, Wavelength Number:

  Case 1:  Wavelength Number = 4
  Case 2:  Wavelength Number = 8
  Case 3:  Wavelength Number = 16
  Case 4:  Wavelength Number = 32

4.3.1. Sample Experiment

In the experiments, we implemented the MILP formulation program with different network parameter values, including different QoS rates, wavelengths, and randomly picked source and destination nodes.
The following demonstrates how we run the experiments and get the result. In this sample experiment, we employed the NSFNET (14 nodes, 21 edges) with 4 wavelengths.

The QoS rates are set as:

- Level-2: 60%
- Level-1: 20%
- Level-0: 20%

We pre-defined the maximum connection number as 1000. If there are not enough resources in the network, the current connection won’t be generated successfully. With failure times equal to or larger than 2, the program will be terminated. At that time, the accomplished connection number will be recorded as the number of successful connections for this test.

Table 4.1. A sample test in NSFNET

Wavelength Number = 4, Node Number = 14, Edge Number = 21.

(QoS rates: Level 2 = 60%, Level 1 = 20%, Level 0 = 20%)

<table>
<thead>
<tr>
<th>Path No.</th>
<th>QoS</th>
<th>Source to Destination</th>
<th>Primary Path</th>
<th>Backup Path</th>
<th>Objective Value</th>
<th>Primary Channel</th>
<th>Backup Channel</th>
<th>Presolve Time (ms)</th>
<th>Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>12 \rightarrow 7</td>
<td>12,11,9, 7</td>
<td>-</td>
<td>3</td>
<td>$\lambda_0$</td>
<td>-</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>12 \rightarrow 0</td>
<td>12,5,2,0</td>
<td>-</td>
<td>3</td>
<td>$\lambda_1$</td>
<td>-</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>7 \rightarrow 9</td>
<td>7,1,2,5, 10,9</td>
<td>7,9</td>
<td>6</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
<td>10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>12 \rightarrow 10</td>
<td>12,13,9, 10</td>
<td>12,5,10</td>
<td>5</td>
<td>$\lambda_2$</td>
<td>$\lambda_3$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3 \rightarrow 6</td>
<td>3,1,2,7, 6</td>
<td>3,4,6</td>
<td>6</td>
<td>$\lambda_1$</td>
<td>$\lambda_3$</td>
<td>10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>8 \rightarrow 5</td>
<td>8,3,4,5</td>
<td>8,11,12,2</td>
<td>5</td>
<td>$\lambda_0$</td>
<td>$\lambda_3$</td>
<td>10</td>
<td>10</td>
</tr>
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</table>

- 43 -
<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>0</th>
<th>5</th>
<th>2</th>
<th>λ₂</th>
<th>λ₀</th>
<th>10</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2</td>
<td>10</td>
<td>2,1,0</td>
<td>2,0</td>
<td>3</td>
<td>λ₂</td>
<td>λ₀</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>10</td>
<td>4,5,10</td>
<td>4,6,7,9,1</td>
<td>5</td>
<td>λ₁</td>
<td>λ₁</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>4</td>
<td>7,6,4</td>
<td>7,9,10,5,4</td>
<td>4</td>
<td>λ₃</td>
<td>λ₁</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>12</td>
<td>3,8,131</td>
<td>2</td>
<td>3</td>
<td>λ₀</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>5,2</td>
<td>-</td>
<td>2</td>
<td>λ₂</td>
<td>-</td>
<td>10</td>
<td>&lt;5</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>5</td>
<td>11,12,5</td>
<td>11,9,10,5</td>
<td>3</td>
<td>λ₀</td>
<td>λ₁</td>
<td>10</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>4</td>
<td>3,4</td>
<td>3,8,11,9,10,5,4</td>
<td>3</td>
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<td>-</td>
<td>1</td>
<td>λ₃</td>
<td>-</td>
<td>&lt;5</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>12</td>
<td>1,2,5,12</td>
<td>-</td>
<td>3</td>
<td>λ₃</td>
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</tr>
<tr>
<td>15</td>
<td>2</td>
<td>8</td>
<td>12,11,8</td>
<td>N/A</td>
<td>3</td>
<td>λ₂</td>
<td>λ₁</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>12</td>
<td>13,12</td>
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<td>λ₃</td>
<td>10</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>4</td>
<td>λ₀</td>
<td>N/A</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>11</td>
<td>4,3,8,11</td>
<td>-</td>
<td>3</td>
<td>λ₂</td>
<td>-</td>
<td>&lt;5</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>8</td>
<td>13,9,11,8</td>
<td>13,8</td>
<td>3</td>
<td>λ₀</td>
<td>λ₃</td>
<td>20</td>
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<tr>
<td>20</td>
<td>1</td>
<td>11</td>
<td>13,8,11</td>
<td>-</td>
<td>2</td>
<td>λ₀</td>
<td>-</td>
<td>&lt;5</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>12</td>
<td>7,1,2,5,12</td>
<td>7,9,11,1</td>
<td>6</td>
<td>λ₀</td>
<td>λ₁</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>7</td>
<td>N/A</td>
<td>3,8,11,9,12</td>
<td>4</td>
<td>N/A</td>
<td>λ₁</td>
<td>20</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>0</td>
<td>3,0</td>
<td>3,8,11,1</td>
<td>4</td>
<td>λ₃</td>
<td>λ₃</td>
<td>10</td>
</tr>
<tr>
<td>24</td>
<td>2</td>
<td>3</td>
<td>12,5,4,3</td>
<td>12,13,8,3</td>
<td>5</td>
<td>λ₀</td>
<td>λ₁</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>13</td>
<td>4,3,8,13</td>
<td>4,6,7,9,1</td>
<td>4</td>
<td>λ₃</td>
<td>λ₁</td>
<td>10</td>
</tr>
<tr>
<td>26</td>
<td>1</td>
<td>4</td>
<td>3,4</td>
<td>-</td>
<td>1</td>
<td>λ₂</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>27</td>
<td>2</td>
<td>10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>30</td>
</tr>
</tbody>
</table>
Table 4.1. A sample test in NSFNET

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average PreSolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,6</td>
<td>8,11,12,5,4,6</td>
<td>4 10</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
</tr>
</tbody>
</table>

In the above experiment, there were 28 successful connections and 2 failures. The details of the successful connections are shown in Table 4.1. A summary of these results is given in Table 4.2.

Table 4.2. Results of the sample test in NSFNET

<table>
<thead>
<tr>
<th>Wavelength Number</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average PreSolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>28</td>
<td>2</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

4.3.2. Experiment Results

In this section, we will provide the summary of our experimental results implemented in NSFNET and ARPANET with the randomly generated values of the three network parameters (including QoS, source node, and destination node for each new required connection).

Experiment I. NSFNET

(QoS rates: Level-2 = 20%, Level-1 = 40%, Level-0 = 40%)

Table 4.3 shows the number of successful connections and processing times for different number of available wavelengths in NSFNET with above specific QoS rates.
<table>
<thead>
<tr>
<th>Wavelength Number</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average Presolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>42</td>
<td>2</td>
<td>9</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>8</td>
<td>96</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>219</td>
<td>2</td>
<td>20</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>32</td>
<td>474</td>
<td>2</td>
<td>69</td>
<td>7</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 4.3. Results of Experiment I

Figure 4.4 shows the number of successful connections versus the number of available wavelengths in NSFNET for experiment I.

![Figure 4.4. Number of Successful Connection for experiment I](image)

The Figure 4.5 shows the processing time (millisecond) of each solution step versus the number of available wavelengths in NSFNET for experiment I.
Figure 4.5. Processing time of each solution step for experiment I

Experiment II. NSFNET

(QoS rates: Level-2 = 60%, Level-1 = 20%, Level-0 = 20%)

Table 4.4 shows the number of successful connections and processing times for different number of available wavelengths in NSFNET with above specific QoS rates.

<table>
<thead>
<tr>
<th>Wavelength Number</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average Presolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>30</td>
<td>2</td>
<td>14</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>85</td>
<td>2</td>
<td>20</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>198</td>
<td>2</td>
<td>43</td>
<td>21</td>
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<tr>
<td>32</td>
<td>455</td>
<td>2</td>
<td>101</td>
<td>36</td>
<td>137</td>
</tr>
</tbody>
</table>

Table 4.4. Results of Experiment II
Figure 4.6 shows the number of successful connections versus the number of available wavelengths in NSFNET for experiment II.

![Bar graph showing the number of successful connections for different wavelength numbers.]

Figure 4.6. Number of Successful Connection for experiment II

The Figure 4.7 shows the processing time (millisecond) of each solution step versus the number of available wavelengths in NSFNET for experiment II.

![Graph showing processing time for different wavelength numbers.]

Figure 4.7. Processing time of each solution step for experiment II
Experiment III. ARPANET

(QoS rates: Level-2 = 20%, Level-1 = 40%, Level-0 = 40%)

Table 4.5 shows the number of successful connections and processing times for different number of available wavelengths in ARPANET with above specific QoS rates.

<table>
<thead>
<tr>
<th>Wavelength Number</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average PreSolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>42</td>
<td>2</td>
<td>12</td>
<td>4</td>
<td>16</td>
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<tr>
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<td>446</td>
<td>2</td>
<td>98</td>
<td>13</td>
<td>111</td>
</tr>
</tbody>
</table>

Table 4.5. Results of Experiment III

Figure 4.8 shows the number of successful connections versus the number of available wavelengths in ARPANET for experiment III.

![Figure 4.8. Number of Successful Connection for experiment III](image-url)
The Figure 4.9 shows the processing time (millisecond) of each solution step versus the number of available wavelengths in ARPANET for experiment III.

![Figure 4.9](image)

Figure 4.9. Processing time of each solution step for experiment III

Experiment IV. ARPANET

(QoS rates: Level-2 = 60%, Level-1 = 20%, Level-0 = 20%)

Table 4.6 shows the number of successful connections and processing times for different number of available wavelengths in ARPANET with above specific QoS rates.

<table>
<thead>
<tr>
<th>Wavelength Number</th>
<th>Number of Successful Connection</th>
<th>Failure Times</th>
<th>Average PreSolve Time (ms)</th>
<th>Average Solution Time (ms)</th>
<th>Average Total Solution Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
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<td>19</td>
<td>8</td>
<td>27</td>
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<tr>
<td>8</td>
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<td>27</td>
<td>16</td>
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<td>32</td>
<td>368</td>
<td>2</td>
<td>108</td>
<td>50</td>
<td>158</td>
</tr>
</tbody>
</table>

Table 4.6. Results of Experiment IV
Figure 4.10 shows the number of successful connections versus the number of available wavelengths in ARPANET for experiment IV.

![Bar graph showing number of successful connections for different wavelength numbers.]

Figure 4.10. Number of Successful Connection for experiment IV

The Figure 4.11 shows the processing time (millisecond) of each solution step versus the number of available wavelengths in ARPANET for experiment IV.

![Line graph showing processing time for different solution steps.]

Figure 4.11. Processing time of each solution step for experiment IV
From the above experiments, we can see that as the number of wavelengths increase, it is possible to accommodate more lightpaths. Also, the solution time increases with the number of available wavelengths since the total solution space is increased.

In the vast majority of cases, the solution time is less than 200ms. This means that our MILP formulation is capable of providing fast dynamic solutions for practical-sized networks.
Chapter 5. Conclusion and Future Work

5.1. Conclusion

In this research, we have proposed a new MILP formulation for dynamic lightpath allocation based on QoS. To find out if this formulation is efficient, we tested it on two well-known network topologies: the NSFNET and the ARPANET. In each scenario, we implemented a program to simulate the physical topology of a network. The program was used to convert the problem described in “3.4.2. Equations of the MILP formulation” into a LP format (executable by the CPLEX system). Then, we invoked the CPLEX optimizer to compute the primary path & backup path (if necessary) for a connection request and their individual wavelengths for each new created path.

From the experiments, we can see that, when the number of available wavelengths is increased, some of the average solution time spent on determining the path solution is decreased (i.e. wavelength number = 8 in experiment I, and wavelength number = 16 in experiment III). That is because that when there are more available wavelengths, it is often possible to route the path along a shorter path. However, in most cases, the solution time still goes up. That is because there are more constraints with the MILP formulation when the available wavelength is increased.

In addition, we find out that the QoS rates affect the number of successful connections in each case. The response time increases when the percentage of level-2 connections is increased (from 20% to 60%). This is because level-2 connections require more
resources than level-0 and level-1 connections since they need to assign extra resources for the backup paths during call setup.

All the experiments on this related problem have showed that this MILP formulation is feasible for practical-sized network, which usually takes less than 200ms. Furthermore, when the launched network size is increased from NSFNET (14 nodes, 21 edges) to ARPANET (20 nodes, 31 edges), the response time is not increased rapidly. This is because the number of constraints in our MILP formulation is O(n).

Based on this study and experiments, we can conclude that in the RWA problem for dynamic wavelength allocation and protection-based scheme, when considering the quality level of connection service, this MILP formulation is simple and efficient. It is capable of providing fast solutions for practical-sized networks.

5.2. Future Work

This formulation solves the RWA problem based on dynamic wavelength allocation and protection-based scheme for the different levels of quality of service. When the service level is at the top priority (level-2), the system will reserve both primary and backup paths for a new connection. However, if the service level is lower (level-0 and level-1), the system won’t pre-define the backup path. If we do need to provide fault-tolerance for the services with lower-levels, we need to consider employing the restoration scheme to provide survivability for level-0 and level-1 services in the future work.
Also, in this thesis, three levels of different services are considered. A new idea has been described about considering different levels of QoS in the survivable WDM networks with the protection-based scheme. One objective is to reduce the amount of idle network resources allocated for backup paths. Potentially, people can define and add more levels of service based on different requests. If necessary, even dedicated-path protection can be employed in this formulation combined with shared-path protection.

In addition, our simulation program can accept multiple requests in the WDM networks. However, the connection requests can only be accepted one at a time. To handle concurrent multiple new connection requests, we need to upgrade our simulation program in the future work.

My opinion is, in a real network construction (e.g. survivable WDM network), it is always advisable to combine different categories schemes together to achieve better performance and more reliability.
Glossary

1. ARPANET - Advanced Research Projects Agency Network
2. CPLEX - C Programming Language + simpEX
3. ILP - Integer Linear Programming
4. LP - Linear Programming
5. MILP - Mixed-Integer Linear Programming
6. NSFNET - National Science Foundation Network
7. OR - Operation Research
8. OXC - Optical Cross-Connect
9. PILP - Pure Integer Linear Programming
10. QoS - Quality of Service
11. RWA - Routing & Wavelength Assignment
12. SONET - Synchronous Optical Network
13. WAN - Wide Area Network
14. WDM - Wavelength Division Multiplexing
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