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Priority based dynamic lightpath allocation in WDM networks.

Suqin Zhong
University of Windsor

Priority Based Dynamic Lightpath Allocation in WDM Networks

By

Suqin Zhong

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Abstract

Internet development generates new bandwidth requirement every day. Optical networks employing WDM (wavelength division multiplexing) technology can provide high capacity, low error rate and low delay. They are considered to be future backbone networks. Since WDM networks usually operate in a high speed, network failure (such as fiber cut), even for a short term, can cause huge data lost. So design robust WDM network to survive faults is a crucial issue in WDM networks.

This thesis introduces a new and efficient MILP (Mixed Integer Linear Programming) formulation to solve dynamic lightpath allocation problem in survivable WDM networks, using both shared and dedicated path protection. The formulation defines multiple levels of service to further improve resource utilization. Dijkstra's shortest path algorithm is used to pre-compute up to 3 alternative routes between any node pair, so as to limit the lightpath routing problem within up to 3 routes instead of whole network-wide. This way can shorten the solution time of MILP formulation; make it acceptable for practical size network. Extensive experiments carried out on a number of networks show this new MILP formulation can improve performance and is feasible for real-life network.

Keywords: WDM, Wavelength Routed Network, lightpath, physical topology, logical topology, Routing and Wavelength Assignment (RWA), protection, restoration, shared path protection, dedicated path protection, MILP, CPLEX, priority, wavelength-link

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Chapter 1

Introduction

With the explosive growth of Internet as well as Internet related services, there is a growing requirement for huge bandwidth. According to recent research, the Internet traffic has approximately doubled every four to six months [CO01]. Fiber optic technology has many advantages such as huge bandwidth, low signal attenuation, small space requirement, and low cost [Muk97]. Therefore fiber optical networks have been employed in main infrastructures to provide services for business, government, military, research as well as other fields. WDM (Wavelength Division Multiplexing) divides the tremendous bandwidth of a fiber (up to 50 Terabits per second) into many non-overlapping wavelengths (WDM channels) [Muk97]. Each channel can transmit different data at any desirable speed, up to 10 Gigabit per second. A single fiber can carry 100 or more wavelengths [AQ00]. The aggregate capacity of a fiber is the number of channels times the rate of each channel. WDM networks are considered to be the future wide-area backbone networks.

However, the huge amount of traffic in a single fiber link also results in tremendous data loss in case of network fault. The most frequent cause for WDM network failure is a fiber cut. Fault tolerant WDM network design has received considerable attention in the last decade. There are two kinds of fault management schemes: Protection and

Restoration. Protection is a predetermined recovery method. In protection, a link disjoint backup lightpath and wavelength are reserved for each primary lightpath during the connection setup phase. In the absence of failures, communication uses the primary lightpath, also called working path. When there is a failure due to a fiber cut, all primary lightpaths using the failed fiber are affected. The affected traffic is rerouted to corresponding backup lightpaths immediately. Protection based strategies can provide quick and guaranteed recovery. But since backup lightpath and wavelength need to be reserved, utilization of network resources is inefficient. Shared path protection scheme, in which resources can be shared among several backup paths, can increase resource utilization. Restoration techniques do not require resources to be reserved in advance. An alternate route and wavelength is found dynamically for each affected lightpath when a failure is detected. Restoration increases network resources utilization, but cannot provide any guarantees on recovery. How to provide efficient fault management strategies is a challenging issue in survivable WDM network design.

1.1 WDM Network Design

WDM network design usually is divided into two sub-problems: network design and Routing and Wavelength Assignment (RWA) problem [XY02].

Network design involves physical topology and configuration design [XY02]. The physical topology of a WDM network consists of Network Access Stations, Optical Cross Connects (OXC), and fiber links. Each access station is equipped with transmitters and receivers to transmit data from or receive data to multiple data sources such as terminal equipment, or local subnetworks. An OXC can route the optical signal coming in on a wavelength of an input fiber link to the same or different wavelength in an output fiber link. Since transmitters, receivers, and OXCs are expensive, each network access station may be equipped with only limited amount of these devices. Physical topology design is to determine the number of Optical Cross Connects (OXC), transmitters and receivers and their interconnectivity in order to provide low-cost and efficient networks.

Logical topology of WDM network is the topology viewed by higher layers such as SONET, ATM, IP [HA00]. Logical topology consists of network nodes and lightpaths. A lightpath is a logical all-optical connection established to satisfy data communication requests between a source node and a destination node. A *lightpath* consists of a route over the physical network and a wavelength (channel) assigned to the lightpath on each link (edge) of that route. In WDM networks without wavelength converters, a lightpath must be assigned same wavelength along all the fiber links it traverses. This is known as *wavelength continuity constraint.* A lightpath provides a single hop communication between a source and a destination node. In an n-node network, if each node is equipped with n-1 transmitters and receivers and if there are enough wavelengths on all fiber links, then every node pair can be connected directly by an all-optical ligthpath [Muk97]. However, as mentioned earlier, transmitters and receivers are expensive, also the number of wavelengths available in a fiber link is limited, and only a limited number of lightpaths can be set up on the network. The logical topology design problem is to determine how to set up lightpaths to accommodate all traffic demand while make optimal use of network resources.

Once the logical topology (for a given physical network and traffic demand) is fixed, we need to map the lightpaths to physical topology and assign wavelengths to them. This is referred to as the Routing and Wavelength Assignment (RWA) problem. RWA will be discussed in detail in Chapter 2.

1.2 Motivations

WDM networks can provide large capacity to satisfy the growing bandwidth demand for many different applications. In the last decade, WDM networks have been traditionally used for long haul, backbone networks. All the lightpaths in the network are known and set up a priori and remain unchanged over relatively long periods of time. However, with the rapid advances in WDM technology, short term or leased lightpaths have become possible. More and more individuals or companies need to lease lightpaths to transmit crucial traffic. Therefore, dynamic lightpath allocation is becoming increasingly important for the future. This thesis focuses on dynamic lightpath allocation in WDM networks. We address the following problems in this thesis:

- Set up lightpaths upon requests dynamically
- Provide backup lightpaths for critical, high priority connections.
- Utilize the idle resources in backup lightpaths
- Make optimal use of resources
- Get solutions in a feasible time for practical sized networks

1.3 Solution Summary and Contributions

In this thesis, we propose a new approach for dynamic lightpath allocation based on path protection, for single fiber fault. We have made two major contributions in the state of the art in this area: (1) we improve the resource utilization efficiency of protection method. (2) We shorten the solution time, making the approach suitable to real life networks.

In order to increase resource utilization, we have introduced 3 different levels of service in our approach. For high priority service (level 2), we reserve a link disjoint backup lightpath and wavelength for each primary lightpath. In case of failure affecting the primary lightpaths, the crucial traffic transmitted on these lightpaths will be rerouted to the corresponding pre-assigned backup lightpath immediately. This guarantees the quick recovery of high priority traffic. For the next level of service (level 1), we need not reserve a backup. The lowest level of service (level 0) also does not have a pre-assigned backup lightpath. Moreover, the primary lightpath can share 'idle' resources assigned to backup lightpaths of high priority services'. This means that under fault free conditions, the idle resources allocated to backup lightpath can be used to transmit low priority traffic. This helps to improve network resource utilization efficiency. However, it also means that these low priority communications may be pre-empted if the associated backup lightpath need to be used.

In order to set up primary and backup lightpaths, we need to find a route for the lightpaths and assign wavelengths to them. This is the typical RWA problem. RWA problem can be formulated as an integer-programming (IP) problem with the objective of optimizing a performance metric of interest [17]. This IP problem has been shown to be NP-hard [17], and very time consuming. The crucial part that affects computation time of an IP problem is the number of integer variables and the number of constraints, which usually grows rapidly with the size of network. In this thesis we have formulated a Mixed Integer Program (MILP) which reduces the number of integer variables by expressing them in terms of continuous variables whenever possible. This minimizes the number of integer variables and makes our formulation feasible for practical sized networks.

1.4 Thesis Organization

The rest of the thesis is organized as follows:

We first present a general review of related background material in Chapter 2. This includes WDM networks, Routing and Wavelength Assignment problem and fault management schemes in optical networks. We also provide a brief introduction of Mixed Integer Linear Program (MILP) and the mathematic tool -CPLEX. Our approach for dynamic lightpath allocation is presented in Chapter 3 and details of the implementation and experimental results are given in chapter 4. Chapter 5 discusses concludes the thesis and gives some directions for future work.

Chapter 2

Background Review

In this chapter, we present a brief review on terminologies and techniques related to the remainder of this thesis. WDM networks, wavelength routed networks, logical topology design and network survivability are introduced in this chapter. Section 2.1 gives the general introduction to WDM networks. Section 2.2 introduces the routing and wavelength assignment (RWA) problem. Section 2.3 discusses different fault management strategies, protection and restoration. Mixed Integer Linear Program (MILP) and the mathematic tool –CPLEX are introduced in Section 2.4.

2.1 WDM Networks

Wavelength Division Multiplexing (WDM) can utilize the tremendous bandwidth available in a fiber by dividing it into many non-overlapping wavelength channels (WDM channel). Each channel can carry different data at any desirable speed, from 2.5 Gigabits to 10 Gigabits per second. The number of distinct channels that can be supported in a fiber depends on fiber characteristics and other technological constraints such as optical components, effect of cross talk on fibers [Muk97]. Now, with the dramatic development of optical technology, 100 or more wavelengths in a fiber is possible [AQ00]. WDM networks can merge data from multiple data sources into a single fiber link so that different data can be transmitted over the same fiber simultaneously. The aggregate network capacity is the number of channels times the rate of each channel. Therefore, WDM allows us to take full advantages of the fiber's huge bandwidth. This sort of WDM network is mainly deployed as a backbone network for large area, e.g., for nationwide or worldwide coverage. End-users can only notice the significantly improved response time and need not know the architecture and operation of the backbone network. Fig.2.1 is an example WDM network. Here, an end-user (Network Access Station) does not need not be terminal equipment, but the aggregate activity from a collection of terminals-including those that may possibly be feeding in from other regional and/or local sub-networks [Muk97].

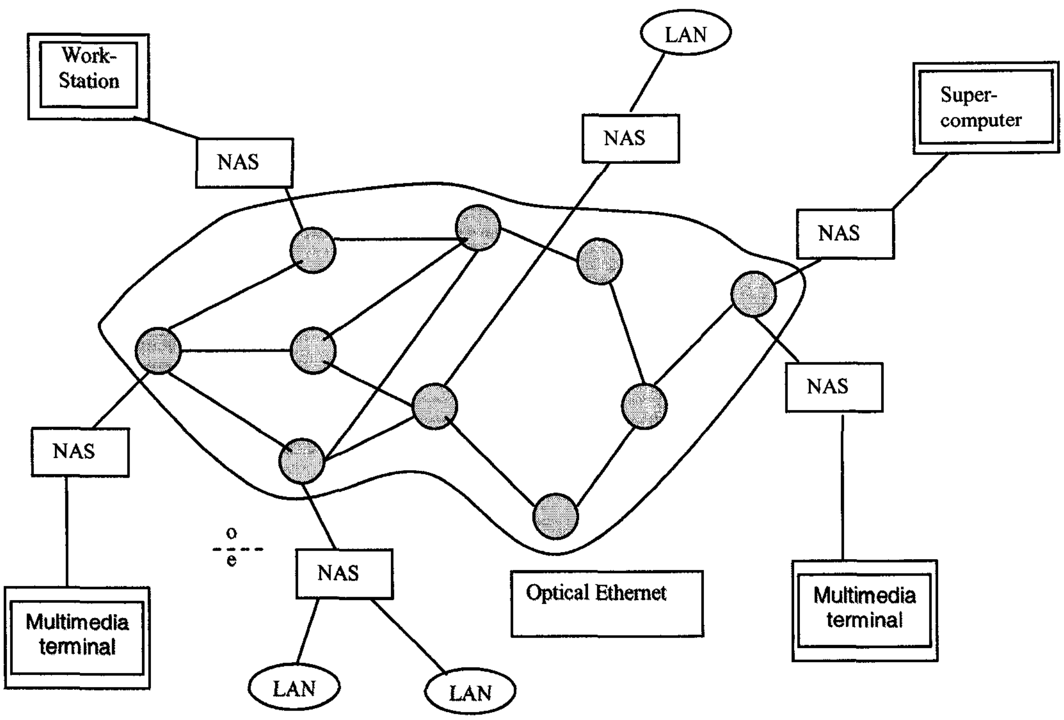


Fig.2.1 WDM network

2.1.1 Physical Topology

The physical topology of WDM network consists of Network Access Stations (NAS), Optical Cross Connects (OXC), and fiber links. As shown in Fig 2.1, access stations connect to OXCs. There are transmitters and receivers in each access station. Access stations transmit signals from different sources (work station, LAN) on different wavelengths. The signals are merged into the fiber by wavelength multiplexers. Access stations also provide optical-to-electronic conversion and vice versa to interface the optical network with conventional electronic equipment [SH02]. OXCs are interconnected by fiber links. Each OXC can route the optical incoming signal on a wavelength of an input port to the same wavelength in an output port. An example OXC is shown in Fig 2.2. If an OXC is equipped with converters, it can switch the optical signal on an incoming wavelength of an input port to any wavelength on an output port.

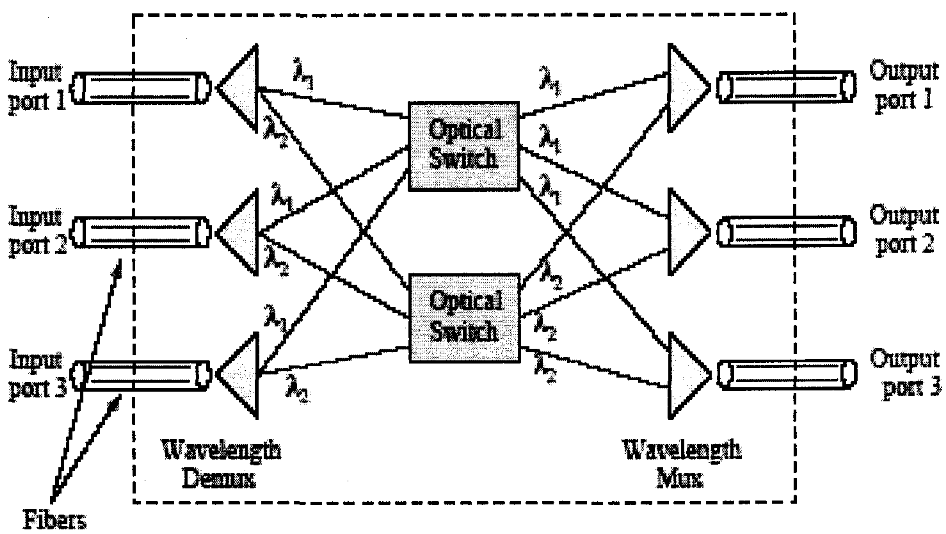


Fig.2.2 OXC

2.1.2 Lightpath

A lightpath [R98], in a WDM network is a end-to end optical communication channel between a source node *s* and a destination node *d* [SJ04]. A lightpath can be viewed as a pipeline between two communicating end nodes with a particular wavelength associated with it. A lightpath may span multiple fiber links [Muk97]. If optical cross connects (OXC) in the WDM network are equipped wavelength converters, a lightpath can use different wavelengths in each fiber link it traverses, otherwise, same wavelength have to be used in all fiber links on the route. This is the well-known *wavelength continuity constraint.* Since wavelength converters are expensive, many works done in the literature, as well as most commercially available WDM networks follow the wavelength continuity constraint. We also consider WDM networks without wavelength converters in this thesis.

Two lightpaths sharing a fiber link should be assigned different wavelength to avoid signal interference with each other. Two or more lightpaths can use the same wavelength as long these lightpaths are link-disjoint. This is called spatial reuse of wavelengths [Muk97]. With spatial reuse of wavelength, although the number of wavelengths available may be limited, the number of lightpaths that can be set up is typically much larger. For example in Fig 2.3, lightpath between node 5 and node 4 spans three fiber links: 5 →S2, S2→S1, S1→4. Following the wavelength continuity constraint, it uses the same wavelength λ_1 on all three links. Since lightpath (5→4) and lightpath (5→1) share fiber link (S2→S1), they have to assigned different wavelengths -- one uses wavelength

λ_1, another uses wavelength λ_2. Lightpath (3→2) is link-disjoint with lightpath (5→4), so λ_1 is reused in lightpath (3→2).

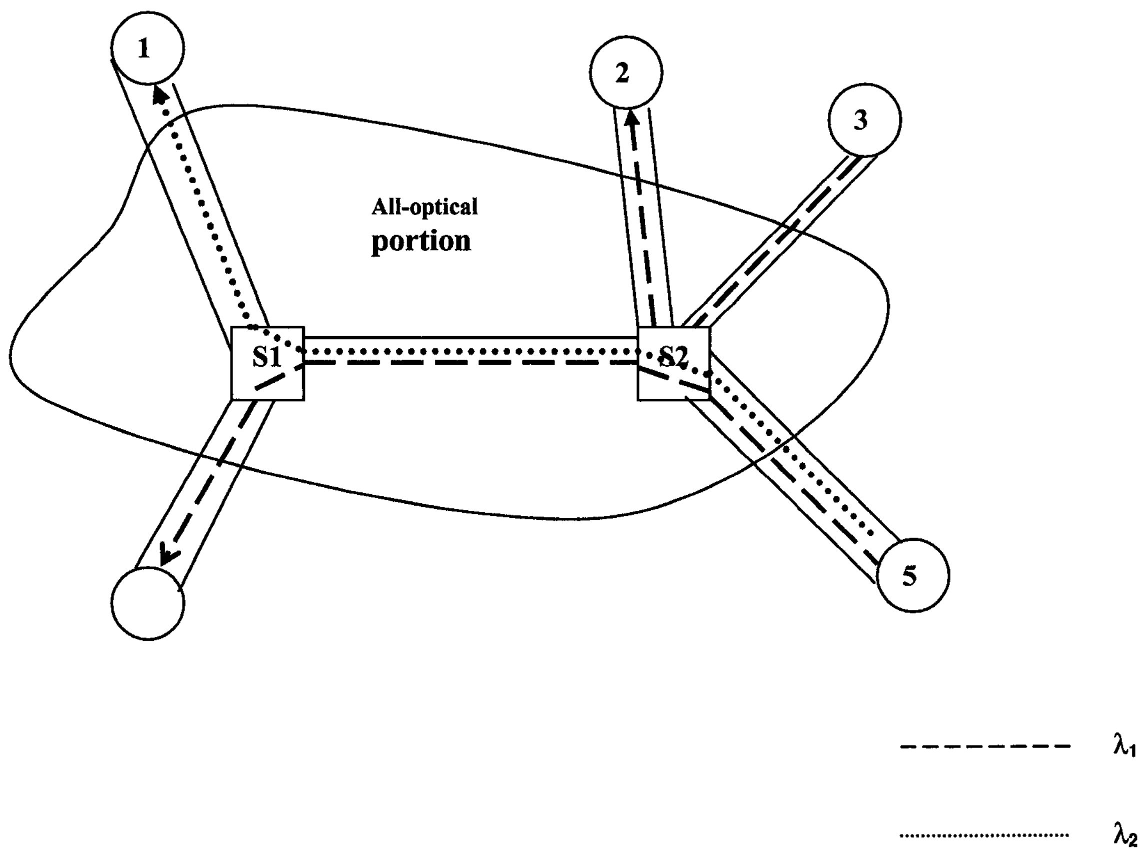


Fig.2.3 A wavelength routed WDM network

2.1.3 Logical Topology

Logical topology [Muk97] of a WDM network, also called virtual topology, is the topology viewed by higher layers. Logical topology consists of network nodes and lightpaths. Fig 2.4 (b) is the logical topology corresponding to the physical topology in Fig 2.4 (a). In Fig. 2.4 (b), nodes correspond to actual physical network nodes as in Fig.2.4 (a), while edges are logical edges, which correspond to lightpaths. Logical topology design looks at the problem of determining how lightpaths should be setup in order to make optimum use of limited network resources. Logical topology design problems have been studied extensively in [MN01][SH02][SB00][HABJ02].

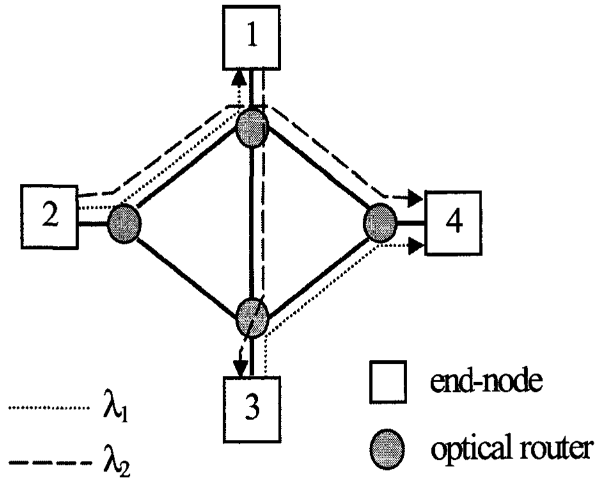


Fig.2.4 (a) Wavelength Routed WDM network (Physical Topology)

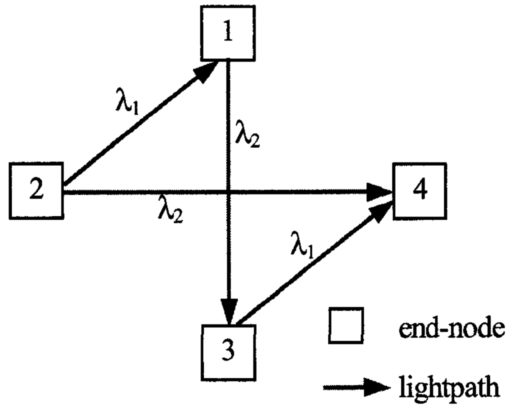


Fig.2.4 (b) Wavelength Routed WDM network (Logical Topology)

2.1.4 Wavelength Routing WDM Network

The commonly used architectural form for WDM networks is Wavelength Routed Networks (WRN) [Muk97], which route signals to the destination based on their wavelengths. In wavelength routing WDM networks, signals are routed in the optical domain, avoiding opto-electronic conversion and processing at intermediate nodes. Therefore, wavelength routing WDM networks avoid the optical-electrical speed mismatch; taking full advantages of a fiber link's huge bandwidth. Fig. 2.3 shows a wavelength routed network containing two WDM optical cross connects (s1, s2) [RM98] and five access stations (1 to 5). The optical cross connects (OXC) route incoming signals to the destination based on their wavelengths and input fiber links. For example, when signal from node 3 on wavelength λ_1 is transmitted to router S2, it will be routed to destination 2 automatically. However, if the signal is from node 5 on wavelength λ_1, it will be routed to destination 4.

2.2 Routing and Wavelength Assignment (RWA)

The Routing and Wavelength Assignment (RWA) problem deals with finding routes for lightpaths in physical topology and assigning wavelengths to the lightpaths [CB98][MS98][MNT01][SH02][SB00]. There are two kinds of RWA problems based on the traffic characteristics. Static traffic has these characters:

- A set of lightpath requests are known in advance
- Lightpaths are set up in advance
- Logical topology remains stable over relatively long periods of time

Static RWA problems find routes and assign wavelengths for the set of given lightpath requests simultaneously. The logical topology usually will not change once decided. This is usually the situation in long haul networks. In dynamic traffic,

- Lightpath requests arrive at and depart from the network randomly
- Lightpath is set up when the request arrives
- Lightpath is destroyed and resources allocated to the lightpath are released after communication is over

Dynamic RWA problems deal with how to dynamically allocate available resources to communication requests so as to satisfy as many as possible communication requests. A lightpath may not be able to setup due to lack of resources, i.e., the lightpath request is blocked. The main goals of dynamic RWA problem are to minimize the blocking probability of the network, and set up lightpaths efficiently within a reasonable amount of time.

RWA problem is typically an optimization problem. There are mainly two kinds of methods to solve RWA problems: heuristic methods and Linear Programming (LP) methods. Heuristic methods usually return sub-optimal solutions requiring a limited computation effort. In many cases, such solutions may be acceptable. Linear Programming (LP) methods are computationally intensive and do not scale well with the network size. Sometimes, the computation time is impractical even with a small network. However, since the LP method can generate absolute optimal solutions, they play a fundamental role either as direct planning tools or as benchmarks to validate and test heuristic methods.

RWA problems have been studied extensively with different goals depending on different limited network resources [ZM00]: (1) satisfy all data communication requests using minimum number of wavelengths (2) create all communication requests using minimum number of fiber links, (3) maximize the number of lightpaths established subject to a constraint on the number of available wavelength and/or path length [Hu03].

2.3 Fault Management Schemes in WDM

There are many sources of WDM network fault, such as fiber cut, noise introduced by optical components, or even cable inside a site getting disconnected. All these are very common reasons that can cause network fault. According to a recent report, Hermes, a consortium of pan-European carriers, estimates an average of one cable cut every four days on their network [XY02]. 136 fiber cuts were reported by various United States carriers to the Federal Communications Commission in 1997 alone [FP98]. A single lightpath usually carries a large amount of traffic (up to 10 Giga bits per seconds), and a fiber can support maybe many lightpaths. Therefore, a single component or cable failure, even for a short duration, will result in much larger data losses than in traditional networks. That is why survivability is always a critical challenge in design and management of WDM networks. Survivable WDM network, also called reliable WDM network, refers to a network that can be resilient to fault, i.e., can still provide the service upon failure occurrences using proper fault management methods. Two main recovery schemes are typically employed: protection and restoration [W92] [W95] [G98].

2.3.1 Protection

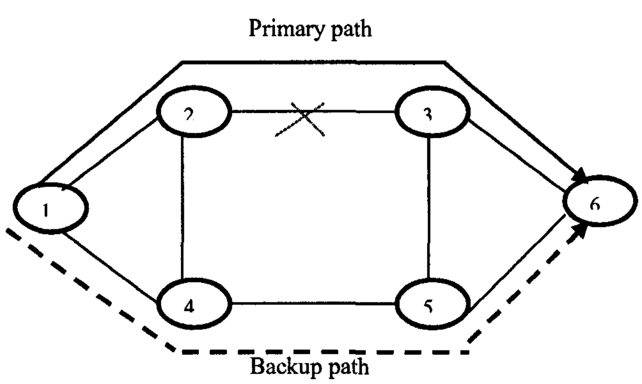
Protection is a proactive procedure in which spare resources are reserved during connection setup. Protection techniques can be classified into path protection versus link protection based on rerouting type, or dedicated protection versus shared protection based on resource sharing.

- **Path Protection**

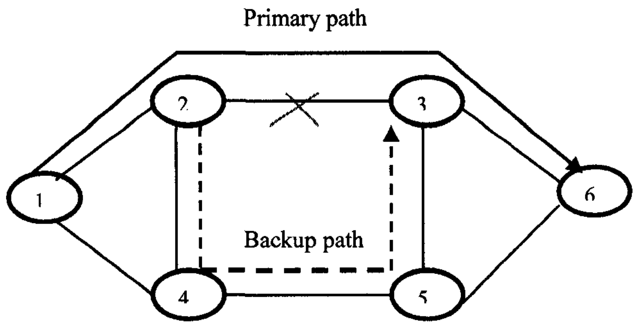
The lightpath carrying traffic under fault-free conditions is called *primary lightpath*. In path protection, during the primary lightpath setup, a link-disjoint backup lightpath is statically reserved between the source and destination nodes. In case of failure occurrence, the affected traffic carried in the primary lightpath will be transferred to the backup lightpath path.

- **Link Protection**

In link protection, the backup lightpath and wavelength are reserved around each link of the primary lightpath. When a certain link fails, the traffic carried in the primary lightpath is rerouted around the failed link only. Source and destination nodes need not be notified of the rerouting. Fig.2.5 shows the difference between path and link protection. Research in [RSM03] shows generally path protection methods are more efficient than link protection methods. We use path protection scheme in this thesis.



Path protection



Link protection

Fig.2.5 Path protection & Link protection

- **Dedicated Path Protection**

Depending on whether the resources allocated to backup paths are shared within several primary lightpaths or not, path protection can be further divided into shared path protection and dedicated path protection. In dedicated path protection, the backup lightpath is reserved for a single primary lightpath; it cannot be used or shared by any other lightpath. It is also referred to as 1+1 path protection [LCC01]. Fig.2.6 is an example of dedicated path protection. In dedicated path protection, backup paths B1, B2 must use different channels. In shared path protection (Fig.2.7.a), they can share same channel λ2 when corresponding primary paths are edge disjoint.

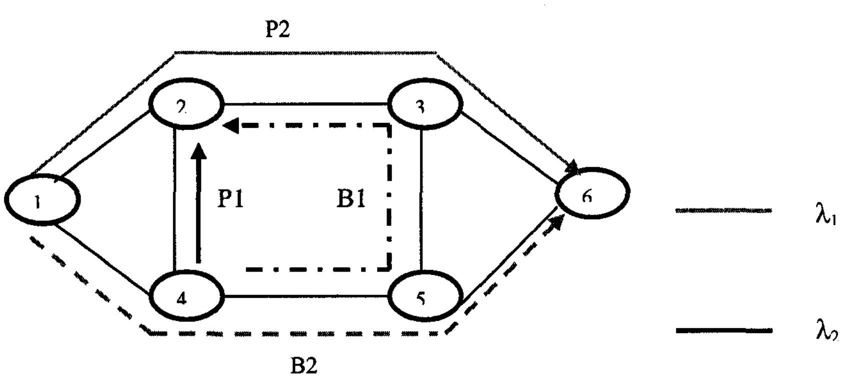


Fig.2.6 Dedicated path protection

- **Share Path Protection**

Capacity utilization of *dedicated path protection* is very low because 100% redundant resources have to be reserved and will be idle when there is no fault in the network. In order to increase capacity utilization, shared path protection was proposed. *Shared path protection* uses *multiplexing techniques*. There are mainly two kinds of multiplexing techniques:

i) *Backup multiplexing*

ii) *Primary-backup multiplexing* [MMS01]

The *backup multiplexing* technique allows two or more backup lightpaths to share a wavelength channel if their corresponding primary lightpaths are link-disjoint. Fig.2.7a shows a shared path protection example using backup multiplexing technique. In Fig.2.7.a, primary lightpaths P1 and P2 are link-disjoint (do not have common fiber links). In the single failure scenario, P1 and P2 cannot both fail at the same time. So their backup lightpaths never need to be used simultaneously. Therefore, the corresponding backup lightpaths B1 and B2 can share same wavelength in their common fiber link 4→5. It is clear, shared path protection methods increase resource utilization.

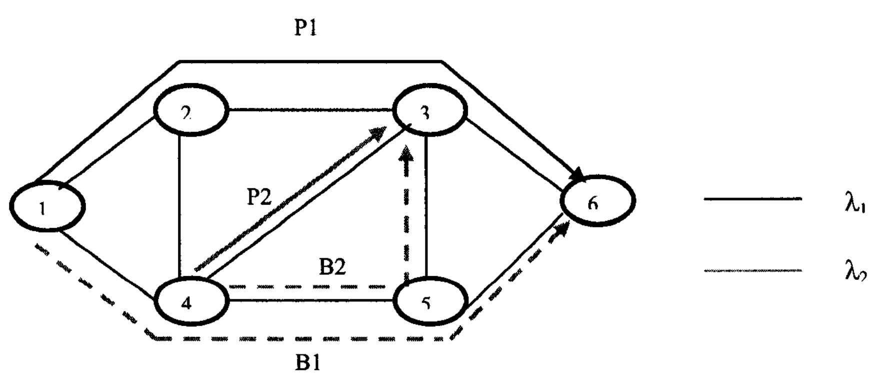


Fig.2.7 (a) Share path protection using backup multiplexing technique

Primary-backup multiplexing technique allows a primary lightpath and one or more backup lightpaths to share a wavelength channel. *Primary-backup multiplexing* technique utilizes the 'idle' resources assigned to backup paths, which decrease the resources redundancy in protection method. The trade off is reduced restoration guarantee on backup lightpath availability for all the failed lightpaths. But once the primary path, which is multiplexed with other backup path, terminates, the backup path will be available immediately. So, primary-backup multiplexing is useful in case of dynamic traffic where lightpaths are short-lived [MMS01]. Fig.2.7 (b) illustrates a shared path protection using primary-backup multiplexing technique. It shows two primary path P1 and P2 and their respective backup paths B1, B2 on a same wavelength channel. The primary path P1 shares the channel on link 4 --> 1 with B2. Channel on link 0 --> 1 is shared by primary path P2 and backup path B1. In this case, both primary path P1 and P2 are nonrecoverable (since their corresponding backup paths are not available). However, if one of them terminates, the other one will be recoverable immediately. Both dedicated and shared path protection are considered in this thesis and both types of multiplexing techniques are used.

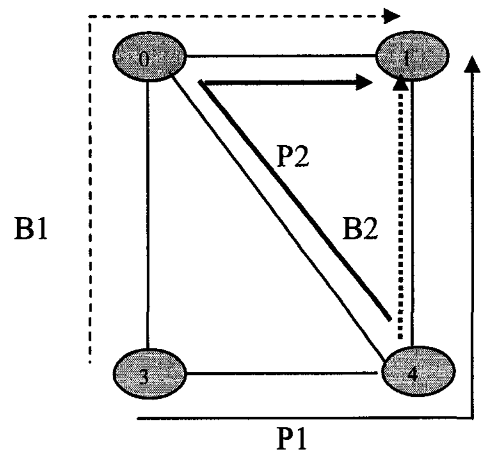


Fig.2.7 (b) share path protection using primary-backup multiplexing technique

2.3.2 Restoration

According to ITU-T (International Telecommunication Union- Telecommunication) Standardization Sector Recommendation G.872 [R99], the technique that reroutes the affected traffic after failure occurrence by using available capacity is referred to as *restoration.* Unlike protection methods reserving resources in advance, restoration methods dynamically search for available resources after the event of a failure. Restoration methods usually have better capacity utilization than protection methods. The trade off is the recovery guarantee. Affected traffic may be dropped due to no resources being available to establish a backup lightpath. Same as protection technique, restoration can also classified as link-based and path-based.

2.4 Mixed Integer Linear Programming (MILP) & CPLEX

As mentioned earlier, the RWA problem is typically an optimization problem. Integer Linear Programs (ILPs) are often used to solve the RWA problem. ILP formulations are typically too time-and-space-intensive [ZOM03]. The crucial factor that affects the computation time of ILP problem is the number of variables, especially number of integer variables. In this thesis, we develop a MILP formulation to solve the RWA problem. In contrast to ILP, in which all variables are integer, in MILP, some variables are continuous variables and some are integers. By reducing the number of integer variables as much as possible, we can greatly shorten the computing time.

2.4.1 MILP

The MILP framework is given below:

Objective Function:

Maximize: (or Minimize)

$$Z = C_1 X_1 + \ldots + Cn\ X_n$$

Constraints:

Subject to: $a_{11}x_{11} + \ldots + a_{1n}x_{1n} \sim b_1$

$$a_{21}x_{21} + \ldots + a_{2n}x_{2n} \sim b_2$$

$$\ldots \ldots$$

$$a_{m1}x_{m1} + \ldots + a_{mn}x_{mn} \sim b_m$$

Bounds:

$$l_i <= x_i <= u_i$$

$$l_n <= x_n <= u_n$$

where ~ can be <=, >= or =, and the upper bounds u_i and lower bounds l_i maybe positive infinity, negative infinity, or any real number.

The data the user provides as input for this LP is:

Objective function coefficients $c_1, \ldots, c_n$

Constraint coefficients $a_{11}, \ldots, a_{mn}$

Right_hand sides $b_1, \ldots, b_m$

Upper and lower bounds $u_1, \ldots, u_n$ and $l_1, \ldots, l_n$

2.4.2 CPLEX

CPLEX is an optimization mathematical software tool for large-scale, mission-critical applications. It can offer high-performance, flexible optimizers for solving linear, mixed-integer and quadratic programming [IL03]. One of its abstracting characters is that CPLEX can solved problems with millions of constraints and variables with very good performance, which is just what we need to solve our MILP problem. Another advantage of CPLEX optimizers is it can be embedded into applications written in Visual Basic, C, Java, and FORTRAN through the *CPLEX Callable Library* [IL03].

When used to solve the MILP problem described in 2.4.1, CPLEX will return the optimal solution and the values of every variable $x_1 \ldots xn$. In this thesis, we use ILOG CPLEX 8.1[IL03] to solve our MILP problem. Details of our MILP formulations and notations will be discussed in chapter 3.

Chapter 3

Priority Based Dynamic Lightpath Allocation

This thesis focuses on dynamic lightpath allocation. In this chapter we will introduce a new and efficient mixed-integer linear program (MILP) formulation for dynamic lightpath allocation in survivable WDM networks, using both shared and dedicated path protection. The formulation can handle multiple levels of service and traditional shared and dedicated path protection schemes can be treated simply as a special case of the formulation. Our objective is to minimize the amount of additional optical resources (wavelength-links) needed for the new connection. We use wavelength-links to represent network resources. This is discussed in detail in section 3.3. We simplify our formulation to shorten the solution time and make it suitable for practical size network by:

- Using Dijkstra's shortest path algorithm to pre-compute up to 3 shortest link-disjoint alternative routes for each node pair
- Defining multiple levels of service

3.1 Pre-compute 3 Link-disjoint Shortest Routes

Assuming a given physical network G (N, E) (N is the set of nodes, E is the set of edges) and a set of available wavelengths **K** on each fiber link, we model our dynamic lightpath allocation problem as a Mixed Integer Linear Program (MILP) with the objective of minimizing the additional amount of network resources (wavelength-links) needed for the new connection. The number of constraints in general formulations usually grows exponentially with the size of network, which makes the solution time of middle size network too long to acceptable. In order to make our approach practical for real-life networks, we use Dijkstra's shortest path algorithm to pre-compute up to 3 shortest link-disjoint alternative routes for each node pair. Then we can select a route for new connection from within these 3 routes, instead of searching the whole network. This greatly limits the number of constraints; therefore shortens the MILP formulation solution time. Two lightpaths are said to be link-disjoint if they do not share any common fiber links in the network. In order to make sure the 3 alternative routes are link-disjoint, we set the edges used in the selected routes as unusable, so these edges will not be used again in the next route for same source-destination pair. Below is the flowchart for creating 3 shortest link-disjoint routes for a given *source-destination* pair.

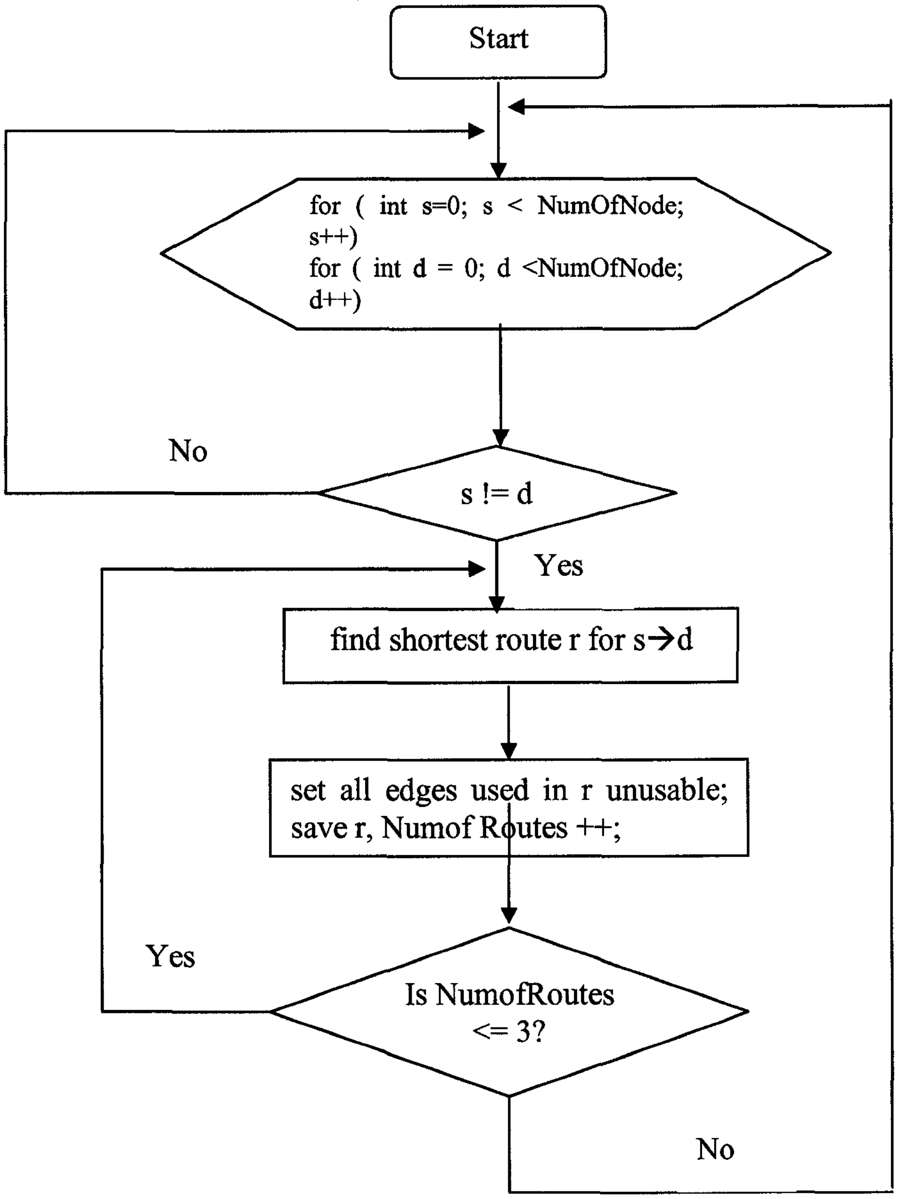


Fig.3.1 Flowchart of find 3 shortest link-disjoint routes

3.2 Define Three Priorities

Protection scheme can provide fast and guaranteed recovery upon network failure, but resources for backup lightpath are redundant under fault-free conditions. In order to further improve resource utilization, we introduce three different levels of service in this thesis:

- **Level 0:** This represents the lowest level of service. No backup lightpaths are provided for this class of primary lightpaths. In addition, resources assigned to these primary lightpaths may also be allocated to (idle) backup lightpaths of higher priority connections, using the same fiber. That means in absence of fault, the idle channels of backup lightpaths of higher priority connections can be used to carry lower priority traffic. The trade off is traffic carried in the level 0 primary lightpath will be dropped when the backup lightpath need to be used, due to a fault.
- **Level 1:** This represents the second level of service. The primary lightpaths of level 1 connections do not share any resources with higher priority backup paths. Therefore, these connections cannot be preempted. However, there is no backup path provided beforehand to handle faults with the primary path. So, restoration techniques need to be used to search for a new route and available channel on that route, once a fault is detected.
- **Level 2**: This represents the highest level of service. At the time of call setup a primary path and an edge-disjoint backup path is determined for each connection. If a fault occurs on a primary path the traffic is automatically switched to the backup path.

We note that the level 0 service traffic will be dropped only when the following three events occur simultaneously: 1) a link fails during the period of level 0 service connection existence; 2) A channel is shared by this level 0 connection and a backup path; and 3) the backup path's corresponding primary path is affected by the failed link. In practice, the chances of this happening are quite small [MMS01]. So, the rate of level 0 service connection being preempted will not be very high.

By defining 3 levels of service, we can use both backup lightpath multiplexing and primary-backup multiplexing [MMS01] in setting up new lightpaths. Backup-multiplexing technology can be used between two level 2 backup lightpaths when their corresponding primary lightpaths are link-disjoint. Primary-backup multiplexing technology can be used between level 0 primary lightpath and level 2 backup lightpath.

3.3 Wavelength-Link

In this thesis, we use wavelength-link to represent network resources. To establish a new connection, we need to find a route between the source and destination nodes and an associated channel on that route. It is clear that the network resources needed for the new connection are the fiber links and channel used on the fiber links. When a wavelength is used on a fiber link, this is one wavelength-link. Fig.3.2 shows an example of how to count wavelength-links and how network resource utilization can be further improved by using 3 levels of service. In this example, P3 (5 --> 3) is a primary lightpath of level 0, using channel λ_1. P1 (0-->1-->2-->3) is a primary lightpath of level 2, with B1 (0-->4-->5-->3) as the backup path, both using channel λ_1. We notice P3 uses the same fiber link 5-->3 with B1. Since P3 is a primary path of level 0 service, so it can share channel λ_1 with B1. The idle channel assigned to backup lightpath B1 now can be used to transmit low priority traffic. Primary-backup multiplexing is used between P3 and B1. P2 (0-->1-->4) is a primary lightpath of level 1 service, using channel λ_2. There is no pre-assigned backup path for P2. P4 (4-->2) is another primary path of level 2 service, using channel λ_2, with B4 (4 -->5 --> 2) as its backup lightpath. Since P1 and P4 are link-disjoint, their backup lightpaths B1 and B4 can share the same channel λ_1 in their common fiber link 4-->5. The wavelength links used in this network are:

- P1 uses λ_1 in fiber link 0-->1,1-->2, 2-->3, wavelength link = 3,
- B1 uses λ_1 in fiber link 0-->4,4-->5, 5-->3, wavelength link = 3
- P2 use λ_2 in fiber link 0-->1,1-->4, wavelength link = 2,
- P3 use λ_1 in fiber link 5-->3, wavelength link = 1,
- P4 use λ_2 in fiber link 4-->2, wavelength link = 1,
- B4 (4-->5-->2) shares λ_1 with B1 in 4-->5, only one additional wavelength-link is needed on fiber link 5-->2. So, wavelength link = 1 (we save one wavelength link).

The total number of wavelength links used in this example is 11.

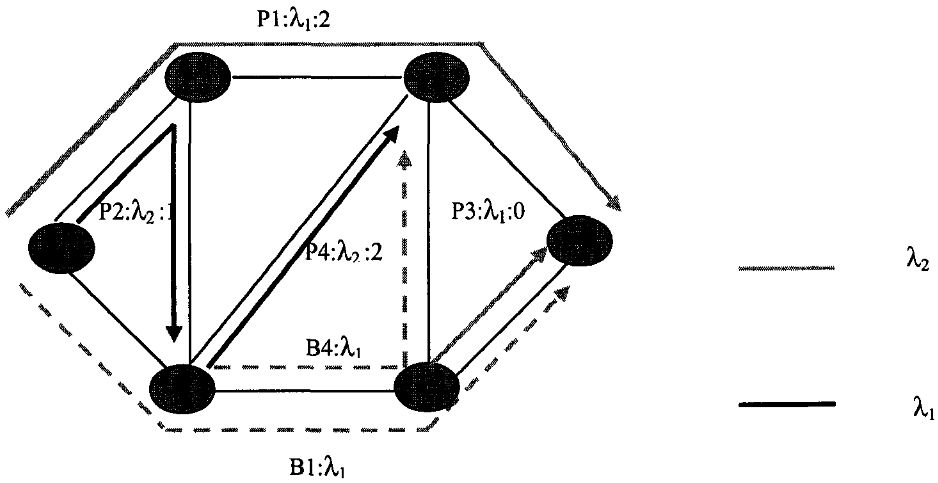


Fig.3.2 Three levels of service (level 0, level 1, level 2)

3.4 MILP Formulations

The MILP formulation given below attempts to find a route and available wavelength for the primary (and if needed the backup) path for the new connection request, when there are P_{max} existing communications currently in progress, each with their own primary (and possibly backup) paths already established. It will be possible to successfully set up the new lightpath if:

i) there exists a route for the primary path and an unused wavelength on that route

ii) there exists (if needed) an available wavelength and a route for a backup path which is edge-disjoint with respect to the primary path for the new connection.

Two lightpaths are said to *share a channel on link e*, if and only if

i) both lightpaths traverse link *e* and

ii) both lightpaths the same wavelength (or channel).

Two lightpaths are said to be *channel-disjoint*, if they do not share a channel on any link in the network.

In this section we will first give the notations and variables used in our formulations for dynamic lightpath allocation. Formulations for i) dedicated path protection ii) shared path protection will be presented in section 3.5 and 3.6.

3.4.1 Notations

The information below is given:

- Physical topology of a fiber network G (N,E) with |N| = n nodes and |E| = m edges.
- The number of channels K that each edge $e \in E$ can accommodate
- The percentage of level 2,level1, level 0 connections

Below are all the notations used in our MILP formulation:

- G [N,E] represents a physical optical network with |N| =n nodes and a set of |E| = m edges.
- A set of channels K (with |K| = k) that each edge $e \in E$ can accommodate.
- A set P of existing connections in the network with $|P| = p_{\max}$
- P^1 represents a list of primary lighpaths that already established, where P^1_p is the p^{th} primary path
- P^2 represents a list of backup lighpaths that already established, where P^2_p is the p^{th} backup path
- $A = (a^p_e)$ is the primary edge-path incidence matrix with:

$$a^p_e = \begin{cases} 1, & \text{if only if the } p^{th} \text{ existing connection uses edge e on its primary path} \\ 0, & \text{otherwise} \end{cases}$$

- $B = (b_e^p)$ is the backup edge-path incidence matrix with:

$$b_e^p = \begin{cases} 1, & \text{if only if the } p^{th} \text{ existing connection uses edge e on its backup path} \\ 0, & \text{otherwise} \end{cases}$$

- $d_e^{sd,r} = 1$, if and only if the r^{th} route between source s and destination d uses edge e.

- k_1^p (k_2^p) is the wavelength assigned to p^{th} primary (backup) lightpath, for all p, $1 \leq p \leq p_{max}$

- $Q^p = \{0,1,2\}$, represents the level of service of the p^{th} existing path

- $Q_{new} = \{0,1,2\}$, represents the level of service of the new connection request

3.4.2 Binary Variables

In this section, we define the binary (0-1 integer) variables that are used in our MILP formulation. For each new connection request, we define two types of binary variables: the route assignment variables x_r, and y_r and the channel assignment variables w_k, and z_k. The route assignment variables determine the how the new lightpaths are routed over the physical topology and the channel assignment variables assign a single wavelength channel to each new lightpath. The variables are defined below.

$$x_r = \begin{cases} 1, & \text{if only if the new connection use the } r^{th} \text{ route to establish the primary path} \\ 0, & \text{otherwise} \end{cases}$$

$$y_r = \begin{cases} 1, & \text{if only if the new connection use the } r^{th} \text{ route to establish its backup path} \\ 0, & \text{otherwise} \end{cases}$$

Here $0 \le r \le R$, R is the number of pre-computed alternative routes between any node pair (s,d), in this thesis R is 3.

$$w_k = \begin{cases} 1, & \text{if channel k is assigned to primary path} \\ 0, & \text{otherwise} \end{cases}$$

$$z_k = \begin{cases} 1, & \text{if channel k is assigned to backup path} \\ 0, & \text{otherwise} \end{cases}$$

We note that if $Q_{new} \neq 2$, then no backup lightpath is needed and $y_r = 0$, for all r, $0 \le r < R$ and $z_k = 0$, for all k, $1 \le k < K$.

3.4.3 Continuous Variables

As discussed in Chapter 1, the crucial part that affects computation time of an IP problem is the number of integer variables. Therefore, we try to minimize the number of integer variables and use continuous variables instead, whenever possible. Even though we define continuous variables for computational advantage, the values of these continuous variables are still restricted to be 0 or 1. In this section, we will list all continuous variables used in our formulation.

$$x_e = \sum_r x_r \cdot d_e^{sd,r} = \begin{cases} 1, & \text{if only if new primary path uses edge e.} \\ 0, & \text{otherwise} \end{cases}$$

$$y_e = \sum_r y_r \cdot d_e^{sd,r} = \begin{cases} 1, & \text{if only if new backup path uses edge e.} \\ 0, & \text{otherwise} \end{cases}$$

This means that x_e (y_e) will have a value of 1 if the new primary (backup) lightpath, from source s to destination d, uses the r^{th} route and edge e is on the r^{th} route. In other words, $x_e = 1$ ($y_e = 1$) if and only if the new primary (backup) lightpath uses edge e.

$$m_{e,p} = \begin{cases} 1, & \text{if only if new backup path multiplexed with } p^{th} \text{ backup path on edge e.} \\ 0, & \text{otherwise} \end{cases}$$

$$\delta_p = \begin{cases} 1, & \text{if only if the new backup path is multiplexed with } p^{th} \text{ backup path} \\ 0, & \text{otherwise} \end{cases}$$

$$c_e = \begin{cases} 1, & \text{if new backup path is multiplexed with another backup path on edge e} \\ 0, & \text{otherwise} \end{cases}$$

Countinuos variables $m_{e,p}$, δ_p, and c_e are only needed in shared path protection and discussed in detail in section 3.6.

3.5 Dedicated Path Protection

In this section, we will describe all physical constraints that have to be satisfied in order to build a new connection using dedicated path protection scheme. The goal is to accommodate the new connection request, using a minimum amount of resources. In our case, this means the minimum number of wavelength links. Since there is no sharing of resources, the number of wavelength links used is obtained simply by adding the number of edges in the primary and backup lightpaths. The MILP formulation for dedicated path protection is given below.

3.5.1 Objective Function

Minimize:

$$\text{Min} \sum_e (x_e + y_e) \tag{3.1}$$

Our objective is to minimize the amount of network resources needed in establishing a new lightpath. $\sum_e x_e$ represents total wavelength-links needed for the new primary path.

$\sum_{e} y_e$ is the total wavelength-links needed for the new backup path. Backup multiplexing technique is not allowed in dedicated path protection. So, the amount of resources needed to setup a new connection is the sum of resources needed by primary path and resources needed by backup path.

3.5.2 Route and Wavelength Assignment Constraints

$$\sum_{r=0}^{R-1} x_r = 1 \tag{3.2}$$

$$\sum_{r=0}^{R-1} y_r = \begin{cases} 1, & \mathit{if}\ Q_{new} = 2 \\ 0, & \mathit{if}\ Q_{new} = 0,1 \end{cases} \tag{3.3}$$

$$x_r + y_r \leq 1, \qquad r = 0, 1 \ldots R-1 \tag{3.4}$$

Equation (3.2) shows among all the pre-computed alternative routes, only one route can be selected as primary lightpath. Equation (3.3) shows among all the alternative routes, only one route can be used as the new backup path when necessary. When the service level of new lightpath is level 0 or level 1, backup path need not to be assigned. So, $\sum_{r=0}^{R-1} y_r = 0$. Equation (3.4) guarantees that the primary and backup lightpath are link-disjoint. Therefore, primary path indicator x_r and backup path indicator y_r cannot be 1 for a given route r at the same time.

$$\sum_{k=0}^{k-1} w_k = 1 \tag{3.5}$$

$$\sum_{k=0}^{k-1} z_k = 1, \quad \text{if } Q_{new} = 2 \tag{3.6a}$$

$$\sum_{k=0}^{k-1} z_k = 0, \quad \text{if } Q_{new} = 0,1 \tag{3.6b}$$

In a WDM network without wavelength converters, wavelength assignment should follow Wavelength Continuity Constraint. Equations (3.5), (3.6a) ensure that only one channel be assigned to the primary (backup) path. Equation (3.6b) applies to cases in which a backup path is not needed (level is 0 or 1 connections).

3.5.3 Primary and Backup Path Link Disjoint Constraints

$$x_e + w_{k_1^p} \leq 1, \quad \forall e \ni a_e^p = 1, \forall p \in P \tag{3.7a}$$

$$x_e + w_{k_2^p} \leq 1, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 1,2 \tag{3.7b}$$

Constraint (3.7a) ensures that the primary path for the new connection is *channel-disjoint* with all other existing primary lightpaths. According to this constraint, x^e and $w_{k_1^p}$ cannot be 1 at the same time. If the new primary path is assigned the same channel with existing p^{th} backup path, i.e., $w_{k_2^p} = 1$, then x^e has to be 0, i.e., it cannot pass the same edge e with p^{th} backup path; vise visa. Similarly, constraint (3.7b) ensures that the new primary lightpath is *channel-disjoint* with all existing backup lightpaths. Clearly, this is only needed if the new connection is level 1 or level 2 (i.e. $Q_{new} = 1$, or 2), since level 0 connections are allowed to share resources with existing (idle) backup paths. Also, this constraint is only applicable if the existing (p^{th}) connection under consideration is a level 2 connection (i.e. $Q_p = 2$) and has an associated backup lightpath.

$$y_e + z_{k_1^p} \leq 1, \forall e \ni a_e^p = 1, \forall p \ni Q_p = 1,2, Q_{new} = 2 \tag{3.8a}$$

$$y_e + z_{k_2^p} \le 1, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.8b)$$

Similar to constraints (3.7a), constraints (3.8a) guarantees a new backup path to be *channel-disjoint* with existing level 1 and 2 primary paths since new backup path can only share channel with level 0 primary path. (3.8b) ensures that the backup path of new connection is *channel-disjoint* with all existing backup paths. These constraints are used only if Q_{new} = 2 since when Q_{new} = 0 or 1, no backup path needed, y_e = 0, constraints are always satisfied. Constraint (8b) is needed because we are considering dedicated path protection, and backup multiplexing is not allowed. This constraint will be removed in the next section, when we consider shared path protection and some new constraints will be added.

3.6 Shared Path Protection

In shared path protection, backup lightpaths are allowed to share resources, if the corresponding primary lightpaths are edge-disjoint. In this section, we will modify our formulation for dedication path protection to handle backup multiplexing. Constraints (3.2) – (3.8a) developed in the earlier section for dedicated path protection, can be applied directly for shared path protection. Constraint (3.8b) is replaced by constraints (3.9a) – (3.12c). Clearly, this is needed only if the new connection request is level 2 (Q_{new} = 2) and the existing connection (p) being considered is also level 2 (Q_p = 2).

3.6.1 Backup Multiplexing Constraints

$m_e^p = 1$ implies that the new backup lightpath is allocated the same channel with the p^{th} existing backup lightpath on a shared edge e. m_e^p, together with variable c_e, indicate if additional resources needed for the current backup path on edge e.

$$c_e = \begin{cases} 1, & \text{if new backup path is multiplexed with another backup path on edge e} \\ 0, & \text{otherwise} \end{cases}$$

The value of c_e indicates whether the new backup lightpath needs additional network resources on edge e. If $c_e = 1$, no additional resources needed on edge e. Clearly, if the new backup lightpath is multiplexed with an existing backup lightpath in edge e, then no new network resources needed to be allocated for the new backup lightpath on edge e, i.e., when $m_e^p = 1$, c_e must be 1.

$$\delta_p = \begin{cases} 1, & \text{if only if the new backup path is multiplexed with } p^{th} \text{ backup path} \\ 0, & \text{otherwise} \end{cases}$$

This variable implies whether the new backup lightpath is allocated the same channel with the p^{th} existing backup lightpath on one or more edges. It is used in constraints (3.11) to ensure that if the current backup lightpath is multiplexed with the p^{th} existing backup lightpath, then the corresponding primary lightpaths are link-disjoint.

$$y_e + z_{k_2^p} - m_{e,p} \le 1, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.9a)$$

$$m_{e,p} - z_{k_2^p} \le 0, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.9b)$$

$$m_{e,p} - y_e \le 0, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.9c)$$

Constraints (3.9a) – (3.9c) are used to define variable $m_{e,p}$. $m_{e,p}$ is a continuous variable, which is set to 1 if and only if the new backup lightpath is allocated the same channel as the p^{th} existing backup lightpath on a shared edge e. Using $m_{e,p}$, constraints (3.10a) – (3.10c) define the variable δ_p such that δ_p=1 if and only if the new backup lightpath and the p^{th} existing backup lightpath share the same channel on one or more edges.

$$m_{e,p} - \delta_p \le 0, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.10a)$$

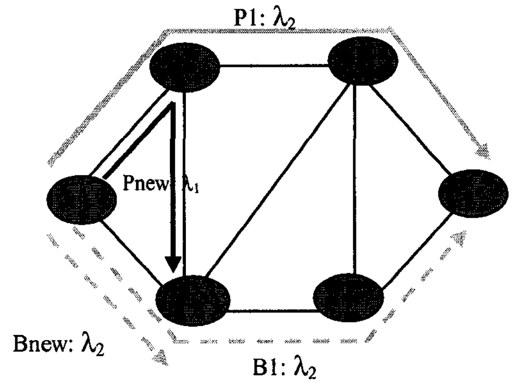
$$\delta_p \le 1, \forall p \ni Q_p = 2 \quad (3.10b)$$

$$\delta_p - \sum_{e \ni b_e^p = 1} m_{e,p} \le 0, \forall p \ni Q_p = 2 \quad (3.10c)$$

If δ_p=1, then we must ensure that the corresponding primary paths are edge-disjoint. This requirement is stated by constraint (3.11).

$$x_e + \delta_p \le 1, \forall e \ni a_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \quad (3.11)$$

Constraints (3.9a) - (3.9c) and (3.11) together ensure the backup multiplexing constraints. The example in Fig.3.3 (a), Fig.3.3 (b) explains backup multiplexing constraints. In Fig.3.3 (a), the new backup path B_{new} uses the same edge (0 --> 4) as existing backup path B1, and shares the same wavelength λ_2. So, $\delta_1 = 1$. According to (3.11), x_e has to be 0 for all edges that the primary path P1 uses, which means that the new primary path cannot use same edge with P1. But as showing in Fig.3.3 (a), p_{new} also uses the same edge (0 --> 1) with P1, which clearly violates constraint (3.11). In this case, if fiber link 0 --> 1 get cut, both primary paths P1 and p_{new} will be affected. Their corresponding backup paths B1 and B_{new} will be needed to be used at the same time. So the channel they shared in edge 0 → 4 will be needed simultaneously. This causes network resource conflict. Therefore, these backup paths multiplexing must use separate channels as showing in Fig.3.3 (b).



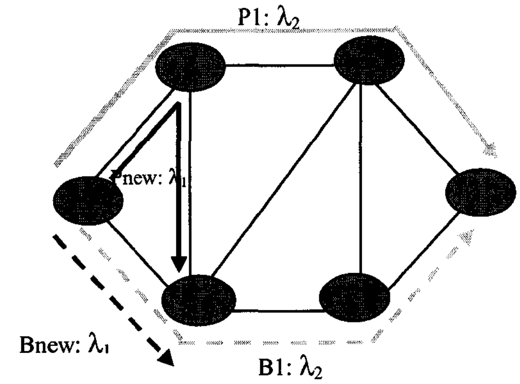


Fig.3.3 (a) Violate backup multiplexing constraint Fig.3.3 (b) Satisfy backup multiplexing constraint

3.6.2 Objective Function

For shared path protection, we also need to modify the objective function so that resources that are shared with existing backup paths do not contribute to the cost more than once. In order to do this, we introduce variable c_e in the objective function. Constraints (3.12a) – (3.12c) are used to define c_e:

$$m_{e,p} - c_e \leq 0, \forall e \ni b_e^p = 1, \forall p \ni Q_p = 2, Q_{new} = 2 \tag{3.12a}$$

$$c_e \leq 1, \forall e \tag{3.12b}$$

$$c_e - \sum_{p \ni Q_p = 2} m_{e,p} \leq 0, \forall e \tag{3.12c}$$

We notice, when $m_{e,p}$=1, which means the new backup path is multiplexing with pth existing backup path on edge *e*, then c_e must be 1. So no additional resource needed for the new backup path on edge *e*.

The new objective function can now be stated as:

Minimize:

$$\text{Min} \sum_e x_e + \sum_e (y_e - c_e) \tag{3.13}$$

Chapter **4**

Experiments and Results

In this chapter, we will describe our implementation to simulate the priority based dynamic lightpath allocation approach described in chapter 3. We have carried out extensive experiments with networks of different size and topology, using several different approaches for dynamic lightpath allocation. A detailed comparison and analysis of the results are presented and used to evaluate the effectiveness of the different approaches.

4.1 MILP Formulation Implementation

In this section, we will describe how we convert the general mathematic equations given in chapter 3 into an appropriate CPLEX recognized format. This is then used by CPLEX to obtain a solution. An example is given to illustrate our approach.

We introduced the MILP formulation for our priority based dynamic lightpath allocation approach in chapter 3. In order to solve the MILP formulation, we have used CPLEX8.1 [IL03], the well-known and efficient optimizers for solving linear, mixed-integer programming. However, CPLEX cannot read the general formulation given in chapter 3. The input file formats CPLEX can read include MPS (Mathematical Programming System) files, CPLEX LP files, and binary files [IL03]. For our experiments, we have used the LP format, which include an objective, a set of variables and a set of constraints.

The number of constraints in the LP format file, for a particular network, depends on a variety of parameters such as network size, available wavelengths each fiber link can carry, etc. It can be of the order of several thousands or even several tens of thousands for large networks. Clearly, it is not feasible to generate LP format file manually. Therefore, we have to implement a program to generate the LP format file automatically. We use C programming language, for our implementation. After generating the LP format file, we call CPLEX functions to solve the MILP problem through the *CPLEX Callable Library*. The main steps in the implementation are given below:

Step I. From an input file, read in the following network specifications:

- The set of nodes
- The set of edges
- The number of wavelengths each fiber link can carry
- The percentage of connections which are of level 2, level 1 and level 0 respectively

Step II. Pre-compute up to R shortest link-disjoint routes for each source-destination pair of the network. Save the route in a 4 dimension array. We use $R = 3$

Step III. Generate a dynamic connection request by randomly generating the following variables:

- Source node s
- Destination node d(must be different from source node)
- Level of service (generating according to percentage of level 2, level 1, and level 0 connections)

Step IV. For each compsite constraint given in chapter 3 (from 3.1 - 3.13), generate the corresponding individual constraints and write into a LP format file - "out_to_cplex". The out_to_cplex file will include:

- Objective function
- All constraints
- Bounds of all variables

Step V. Using "out_to_cplex" as the input file, call CPLEX to solve this MILP problem. The solution includes optimal objective value and values of all variables:

- $x_i = 1$ indicates that i^{th} route is used as the primary lightpath for the new connection between *s-d*
- y_j =1 indicates that j^{th} route is used as the backup lightpath for the new connection between *s-d* (if level of service = 2)
- w_k = 1 indicates that channel k is assigned to the primary lightpath of new connection
- z_l = 1 indicates that channel l is assigned to the backup path (if necessary)
- c_e = 1 implies the cost of the backup path is saved on edge e (not suitable for the first lightpath)
- m_e^p = 1 implies the backup path is multiplexing with p^{th} backup path on edge e (not suitable for first lightpath)

Step VI. Update the logical topology of the network, by adding this connection to the set of existing connections and repeat step III - VI

Step VII. This procedure ends when:

- either the maximum number (given as an initial constant) of lightpaths have been establishes successfully
- Or number of failures is great than 2, which implies network is becoming congested

4.1.1 An Example

In this section, we give an example to solve dynamic lightpath allocation problem in a 3-node network (Fig.4.1) using shared path protection approach.

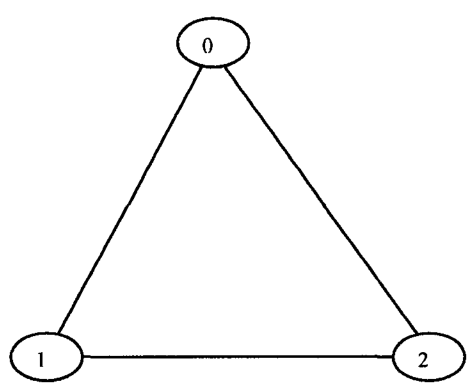


Fig. 4.1 Input 3-node network topology

Step I. Input parameters. The input file includes 3 lines:

3 3 4

60 20 20

0 1 0 2 1 2

First line indicates this is a network with 3 nodes and 3 (bi-directional) edges; each edge can carry 4 channels. The second line is the percentage of the 3 service levels, level 2 is 60%, level 1 is 20%, and level 0 is 20%. The third line indicates the physical topology of this network, i.e, there are edges between nodes 0 and 1, 0 and 2, 1 and 2. The edges in the network are bi-directional, i.e., each edge consists of two separate fiber links in opposite directions. So, there are 6 unidirectional edges in the input network. The edges are numbered as follows:

edge0: 0 --> 1

edge1: 1 --> 0

edge2: 0 --> 2

edge3: 2 --> 0

edge4: 1 --> 2

edge5: 2 --> 1.

Step II. Compute up to 3 shortest routes between each node pair and save them in array variable *route*[source][destination][route#][edge]. For example, Route 0 from node 0 to node 1 uses edge 0 (0-->1), the corresponding entries in the array are:

route [0][1][0][0] = 1
route [0][1][0][1]=0
route [0][1][0][2]=0
route [0][1][0][3] = 0
route [0][1][0][4]=0
route [0][1][0][5]=0

Step III. Randomly generate connection 0: from node1 to node 2, with service level=2.

Step IV. Produce the LP format file corresponding to the formulation in chapter 3.

Step V. Call CPLEX to solve the problem. The following solution is generated:

- Objective value = 3.000000 - which is the minimum cost (wavelength links) for building the new primary path and backup path from 1 --> 2.
- x0 = 1, indicates route 0 between 1 -->2, which passes though edge 4 (1 -->2) is used as primary path. So, the cost for primary path is 1.
- y1 = 1, indicates route 1 between 1 -->2, which passes though edge 1 (1 -->0) and edge 2 (0 -->2), is used as backup path. The cost for backup path is 2. So, total cost for path 0 equals 3- objective value.
- w0 = 1, channel 0 is assigned to primary path P0
- z0 = 1, channel 0 is assigned to backup path B0

Step VI. After establishing the first path p0 and its backup path b0, the logical topology of the original network has changed. Now, in the network, there is a primary path and a backup path, both use channel 0 showing in Fig.4.2.

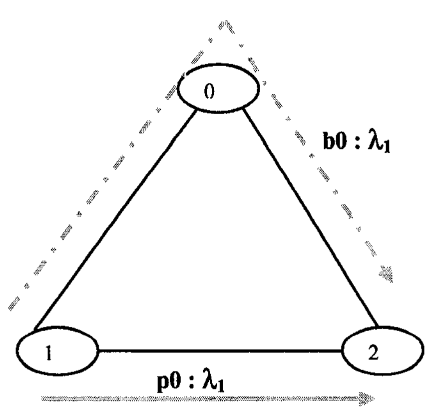


Fig.4.2. topology after setting up 1 level 2 service connection (1-->0)

Similarly a second connection request is generated from node0 to node1, with service level 2. After creating the LP format file and solving with CPLEX, the following solution is generated:

- Objective value = 2, the minimum cost (wavelength links) for building the new primary path and backup path from 0 --> 1.
- x0 = 1, route 0 between 0 -->1, which passes edge 0 (0 --> 1) is used as primary path. The cost for primary path is 1.
- y1 = 1, route 1 between 0 --> 1, which passes though edge 2 (0 --> 2) and edge 5(2 --> 1) is used as backup path.
- c2 = 1, indicates the cost for backup path on edge 2 (0 --> 2) can be saved.
- w1 = 1, channel 1 is assigned to primary path P1.
- z0 = 1, channel 0 is assigned to backup path B1.
- m2_0 = 1, implies that the new backup path B1 is multiplexing with 0^{th} backup path B0 on edge 2 (0 → 2), so the cost of backup path B1 on edge 2 is saved.

Fig.4.3 shows the topology after setting up the lightpaths corresponding to the above two connection requests. P0 and p1 are link disjoint, so their backup paths share same channel 0 on link 0 → 2, backup multiplexing technique is used to save one wavelength channel.

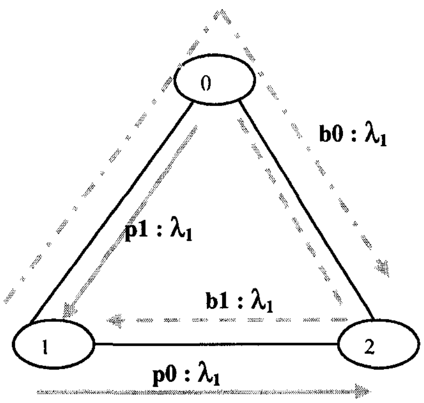


Fig.4.3 Topology after setting up two level 2 connections

4.2 Experiments

We have tested our formulation on a large number of networks under different conditions. The experiments were designed to test:

i) if the performance (solution time) is acceptable even when dealing with larger networks

ii) if introducing multiple levels of service significantly improves resource utilization in the network.

All experiments were carried out on a 350 MHz Sun Solaris server with 14 processors, using CPLEX 8.1 [IL03]. The network sizes range from 6 nodes to 53 nodes. These include the well-known 14-node NSFNET [SSS02], 20-node ARPANET [IMG98] and other networks used in the literature [IMG98]. Topologies of the tested networks are shown in appendix B.

4.2.1 Testing Strategies

We use 5 approaches in our experiments: 1) *Shared 3 levels* of service; 2) *Shared single level of service;* 3) *Dedicated 3 levels* of *service;* 4) *Dedicated single level* of *service* and 5) *Shared without pre-computed routes* [Hu03]. Approach (1) and (2) are based on shared path protection scheme. Backup multiplexing and primary-backup multiplexing techniques are used in shared approach. Approach (1) considers 3 levels of service level2, level1, and level 0. Approach (2) is the traditional shared path protection scheme, which has single level of service, and can be treated as a special case of approach (1). Approach (3) and (4) are *dedicated approaches* without resource sharing in backup lightpaths. One is with 3 levels of service; the other is traditional dedicated approach with single level of service. Approach 5 is proposed in [Hu03]. In this approach, the routes for primary lightpath or backup path of new connections are searched in the whole network instead of within 3 pre-computed routes. We pre-define two constraints MAX-LP and MAX-FAILURE. When a connection request fails MAX-FAILURE times, we assume the network is getting congested and terminate the program; otherwise, the program will be terminated when MAX-LP number of connections are established. In our experiments we have used MAX-LP = 2000 and MAX-FAILURE = 2.

4.2.2 Experiment Results

Tables 4.1 - table 4.6 show the number of successful connections, average wavelength link, wavelength link utilization, active wavelength link utilization, and solution time for each approach on different networks.

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (s)
Share, 3 levels of service	4	14	2.61	57.7	1.73	38.8	0.0288
	8	33	2.72	67	1.76	43.4	0.0374
	16	65	2.67	67.8	1.68	42.9	0.0635
	32	141	2.64	72.5	1.69	46.4	0.1397
	64	301	2.6	76.6	1.62	47.7	0.3915
Share, single level of service	4	12	3.49	57.2	1.86	32	0.0406
	8	23	3.54	61.3	1.84	31.7	0.0514
	16	46	3.54	63.7	1.87	33.7	0.1003
	32	99	3.36	65.1	1.8	34.8	0.2473
	64	224	3.3	72.3	1.72	37.6	0.906
Dedicate, 3 levels of service	4	13	2.82	57.2	1.7	35.2	0.027
	8	25	3.08	60.4	1.68	33.1	0.0258
	16	57	2.97	66.4	1.65	37	0.0279
	32	119	2.98	69.6	1.61	37.7	0.0365
	64	258	3	75.6	1.55	39.1	0.067
Dedicate, single level of service	4	8	3.92	46.6	1.9	23	0.0293
	8	18	4.07	56.6	1.78	24.8	0.0273
	16	39	4.06	61.9	1.72	26.3	0.0287
	32	83	3.93	63.2	1.66	26.7	0.0389
	64	188	3.9	71.6	1.62	29.8	0.081
Shared, without pre-computed routes	4	16	2.74	66.6			0.0462
	8	33	2.79	69.8			0.0671
	16	69	2.67	71.3			0.1118
	32	148	2.53	72.9			0.2504

Table 4.1 Experiment results in 6-node network

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (s)
Share, 3 levels of service	4	46	2.48	64.4	1.74	45.2	0.0402
	8	108	2.34	71.6	1.73	52.8	0.0898
	16	260	2.16	79.6	1.68	61.9	0.2729
	32	523	2.15	80	1.7	63.1	0.9348
	64	1111	2.09	82.6	1.67	66.1	2.703
Share, single level of service	4	36	2.96	59.8	1.88	38	0.0553
	8	80	2.78	62.5	1.84	41.4	0.1707
	16	186	2.58	68	1.78	46.8	0.634
	32	387	2.54	69	1.81	49.7	2.165
	64	811	2.44	70.2	1.77	50.1	6.677
Dedicate, 3 levels of service	4	37	2.78	57.6	1.89	39.2	0.0271
	8	74	2.92	61.1	1.93	40.5	0.0295
	16	169	2.86	68.7	1.8	45.5	0.0327
	32	351	2.91	72.4	1.9	47.2	0.0381
	64	694	2.96	72.8	1.93	48	0.039
Dedicate, single level of service	4	22	3.79	46.1	2.25	27.4	0.0259
	8	49	3.81	52.9	2.21	30.7	0.0307
	16	114	3.76	60.6	2.17	35.1	0.0341
	32	242	3.78	65	2.16	37.2	0.0393
	64	513	3.73	67.9	2.08	38	0.0415
Shared, without pre-computed routes	4	58	2.38	78.4			0.1033
	8	130	2.22	82.1			0.2864
	16	301	2.06	88			0.967
	32	621	2.05	90.5			3.6

Table 4.2 Experiment results in 10-node network

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (s)
Share, 3 levels of service	4	26	3.69	55.4	2.5	37.7	0.048
	8	65	3.46	63.3	2.42	44	0.0955
	16	155	3.18	70	2.33	51.2	0.314
	32	329	3.15	73.1	2.35	54.8	1.437
	64	700	3.07	76.4	2.32	57.8	4.273
Share, single level of service	4	21	4.5	54.1	2.72	34.1	0.058
	8	50	4.17	59.5	2.77	36.9	0.191
	16	113	3.84	61.6	2.44	41.1	0.97
	32	261	3.63	66.5	2.38	43.6	2.111
	64	511	3.71	67.3	2.52	45.7	9.823
Dedicate, 3 levels of service	4	20	4.24	46.8	2.48	29.5	0.0216
	8	49	4.16	57.4	2.41	35.2	0.0345
	16	103	4.18	60.9	2.44	37.4	0.037
	32	206	4.21	62.4	2.76	40.9	0.047
	64	463	4.23	69.2	2.66	43.7	0.049
Dedicate, single level of service	4	15	5.1	45.5	3.49	29.3	0.033
	8	32	5.54	49.5	3.39	30.1	0.034
	16	67	5.55	52.9	3.42	32.7	0.038
	32	160	5.21	57.7	3.2	35.8	0.046
	64	294	5.6	62.7	3.27	37	0.047
Shared, without pre-computed routes	4	34	3.53	67.8			0.12
	8	77	3.3	72.3			0.359
	16	170	3.17	76.8			1.152
	32	379	3	80.6			3.437

Table 4.3 Experiment results in 14-node NSFNET

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (ms)
Share, 3 levels of service	4	26	4.98	52.9	3.3	34.6	30
	8	54	4.9	53.9	3.33	36.3	63.1
	16	116	4.83	56.5	3.31	38.7	189
	32	257	4.62	59.9	3.21	41.5	682
	64	443	4.59	61	3.19	45	2549
Share, single level of service	4	20	6.19	49.9	3.34	27.4	49.9
	8	40	6.09	51.6	3.58	30.4	132
	16	86	5.93	51.7	3.47	30.4	429
	32	190	5.83	53.4	3.46	31.7	1539
	64	373	5.8	54.5	3.4	32	6988
Dedicate, 3 levels of service	4	21	5.43	46	3.43	29	20.5
	8	44	5.47	47.8	3.43	30	20.7
	16	92	5.48	50.8	3.45	31	22.3
	32	182	5.7	52.2	3.5	32	27
	64	362	5.8	52.9	3.53	32.3	59
Dedicate, single level of service	4	14	7	39	3.67	20.7	21.6
	8	26	7.55	39.9	4.1	21	21.7
	16	65	6.2	40	3.26	21.3	23
	32	111	7.28	40.7	3.82	21.4	29
	64	222	7.32	41	3.82	21.8	63
Shared, without pre-computed routes	4	33	4.06	62.9			162
	8	70	3.98	65.2			454
	16	156	3.92	69.1			1527
	32	323	3.75	70.4			4467

Table 4.4 Experiment results in 20-node ARPANET

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (ms)
Share, 3 levels of service	4	34	5.27	37.4	3.52	24.9	41.2
	8	81	4.8	40.9	3.3	28.1	83.9
	16	171	4.67	42.4	3.32	30.1	274
	32	407	4.5	48.4	3.32	35.7	799
	64	916	4.44	53.9	3.34	40.5	3161
Share, single level of service	4	29	6.28	38.6	3.66	22.5	60.5
	8	65	5.63	38.4	3.36	23	171
	16	137	5.5	39.8	3.45	25	642
	32	325	5.39	46.4	3.51	30.3	2099
	64	565	4.95	37	3.31	24.8	8004
Dedicate, 3 levels of service	4	28	5.6	33	3.6	21.6	24.9
	8	60	5.4	34.3	3.43	21.8	31.4
	16	129	5.51	37.8	3.49	24	35.9
	32	259	5.61	38.5	3.55	24.3	42
	64	576	5.56	0.424	3.38	25.8	62
Dedicate, single level of service	4	18	7.4	27.8	4.06	15.3	27.7
	8	43	6.86	31	3.76	17	31.9
	16	87	7.07	32.6	3.84	17.8	36.8
	32	191	7.15	36.2	3.84	19.4	42
	64	346	7.06	32.4	3.71	17	61
Shared, without pre-computed routes	4	58	4.78	58.4			351
	8	140	4.46	66.2			1709
	16	305	4.29	69.2			6975
	32	484	3.84	49.2			345000

Table 4.5 Experiment results in 30-node network

Approach	Number of wavelength	Number of successful connections	Average wavelength link	Wavelength link utilization (%)	Active wavelength link	Active wavelength link utilization (%)	Average solution time (ms)
Share, 3 levels of service	4	15	9.49	21.1	5.83	13.1	39.6
	8	32	9.46	23.3	5.88	14.5	56.7
	16	67	9.25	24.2	5.83	15.3	112
	32	156	9.36	28.5	5.76	17.6	438
	64	358	9.16	32	5.68	19.8	1415
Share, single level of service	4	11	12.72	22	6.5	11.3	51.8
	8	25	12.19	23.5	6.29	12.2	95
	16	51	12.44	24.7	6.34	12.6	244
	32	125	11.98	29.2	6.56	16	786
	64	268	11.67	30.5	6.12	16	2271
Dedicate, 3 levels of service	4	13	9.9	19.6	5.9	11.4	30.1
	8	28	10.3	22.3	5.65	12.3	30.2
	16	60	9.96	23.2	5.59	13.1	33.5
	32	115	10.5	23.7	5.73	12.9	34
	64	294	12.1	28.9	5.6	16.2	67
Dedicate, single level of service	4	9	13.39	18	6.03	7.99	30.0
	8	20	13.95	21.2	5.77	8.75	32.5
	16	42	13.56	22	5.57	9.03	36
	32	87	13.6	23.1	5.45	9.2	36
	64	189	14.05	25.3	5.73	10.1	80
Shared, without pre-computed routes	4	22	9.31	33.3			333
	8	45	9.35	32.8			1369
	16	97	9.04	34.2			4120
	32	200	8.74	34.1			10241

Table 4.6 Experiment results in 53-node network

4.2.3 Experimental Results Analysis

1) Number of connections

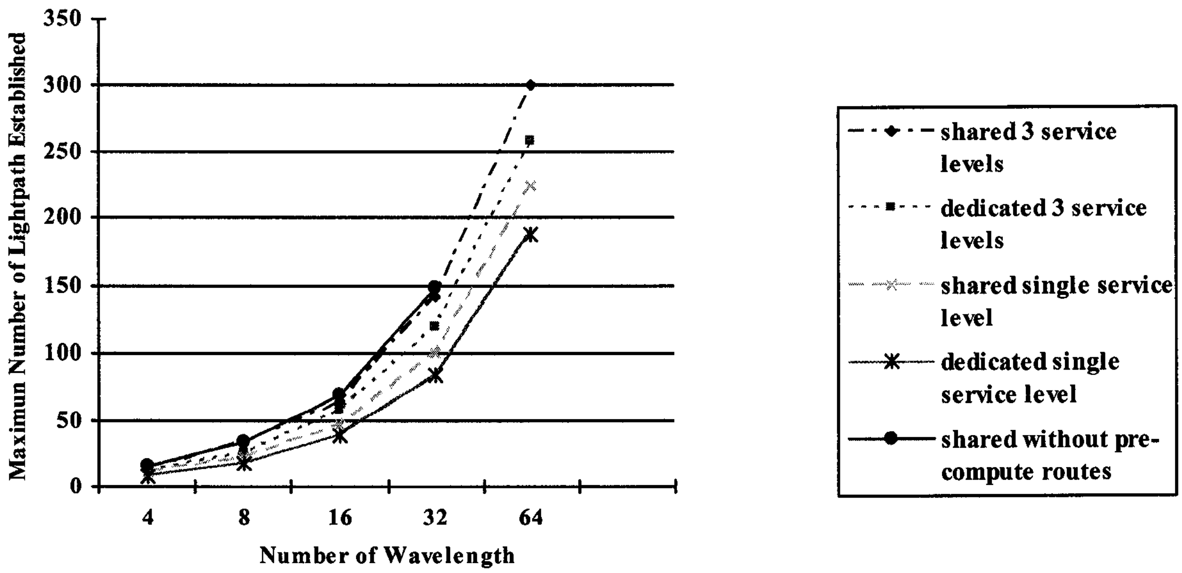


Fig.4.4 No. of connections vs. wavelengths in 6-node network

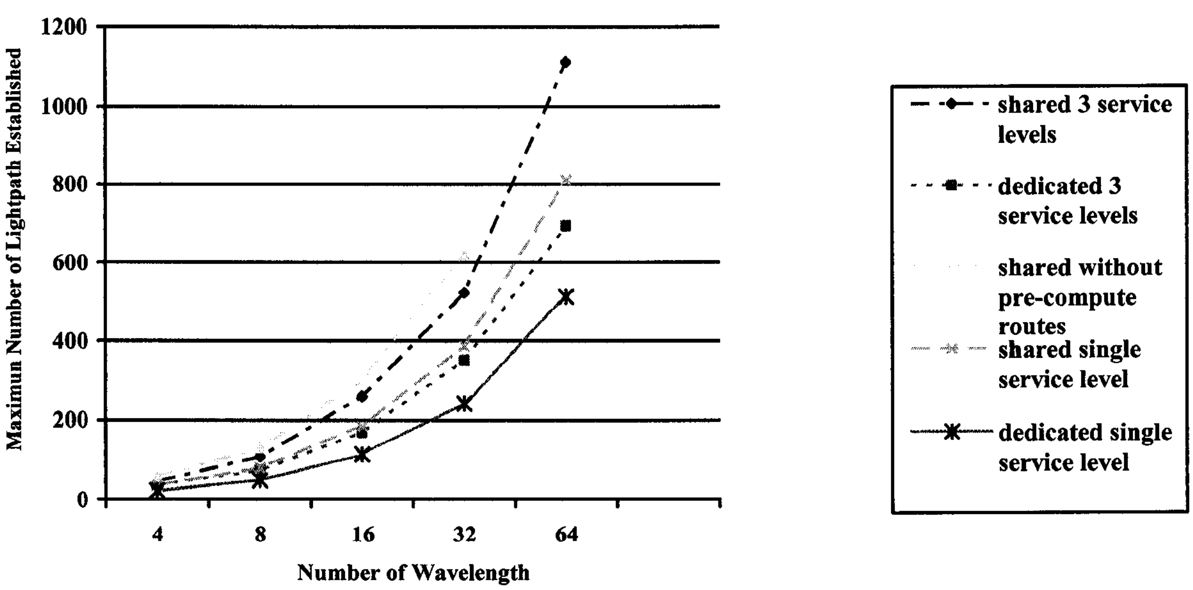


Fig.4.5 No. of connections vs. wavelengths in 10-node network

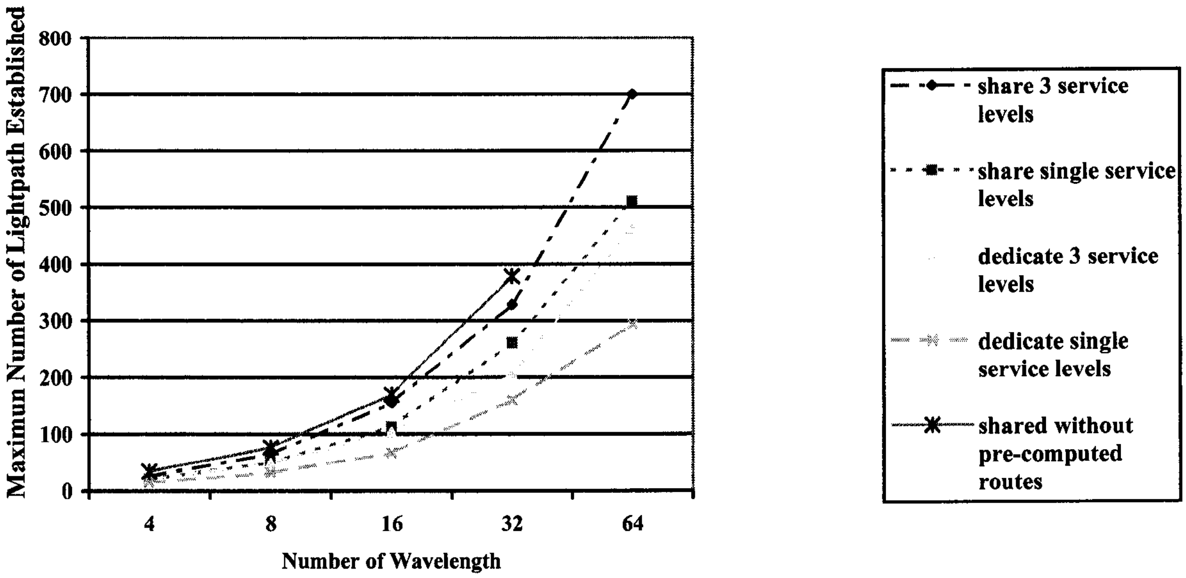


Fig.4.6 No. of connections vs. wavelengths in 14-node NSFNET

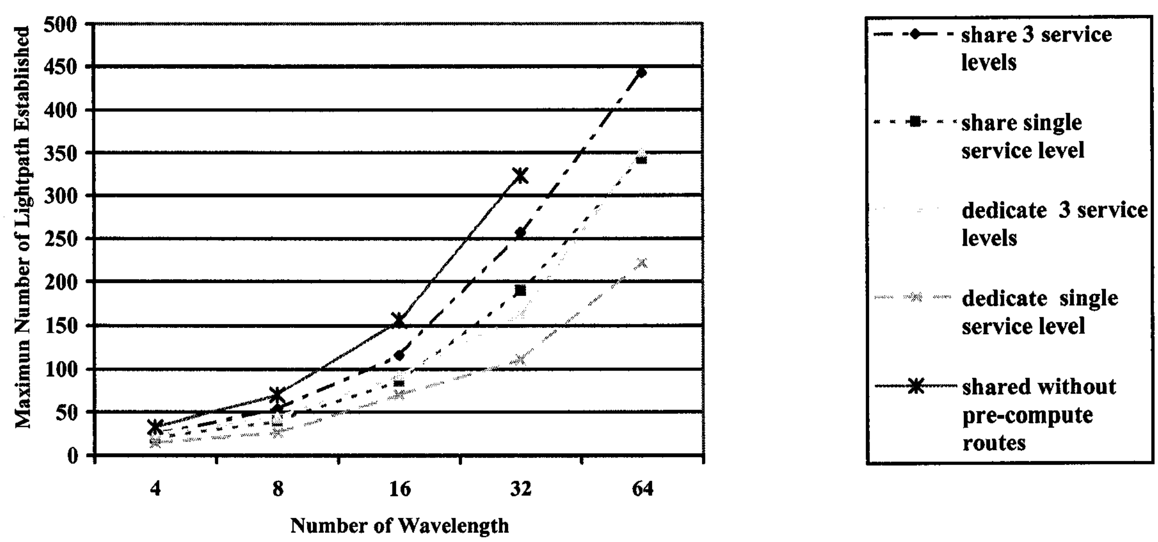


Fig.4.7 No. of connections vs. wavelengths in ARPANET

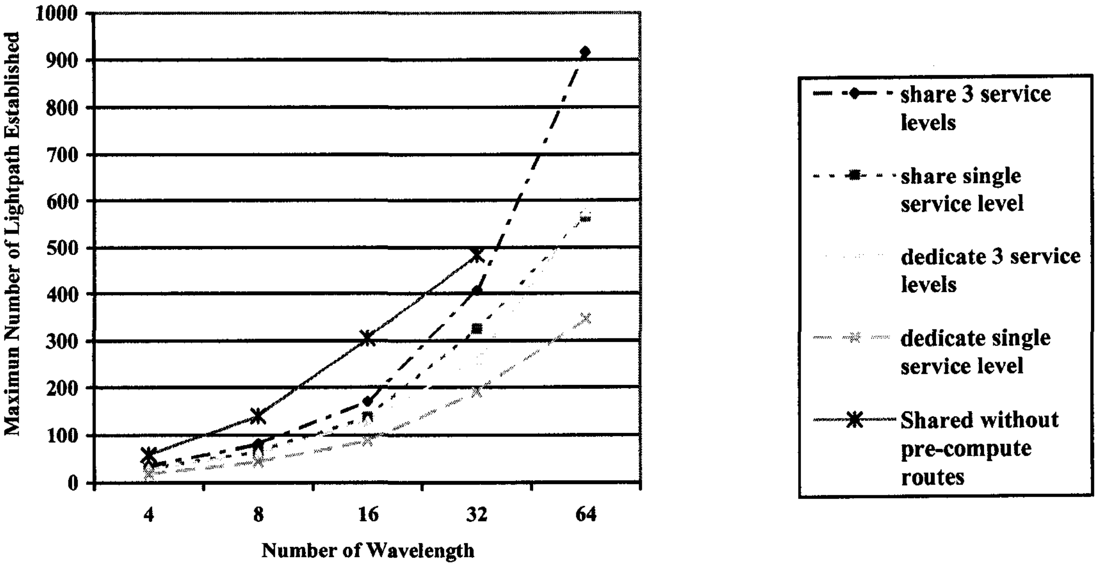


Fig.4.8 No. of connections vs. wavelengths in 30-node network

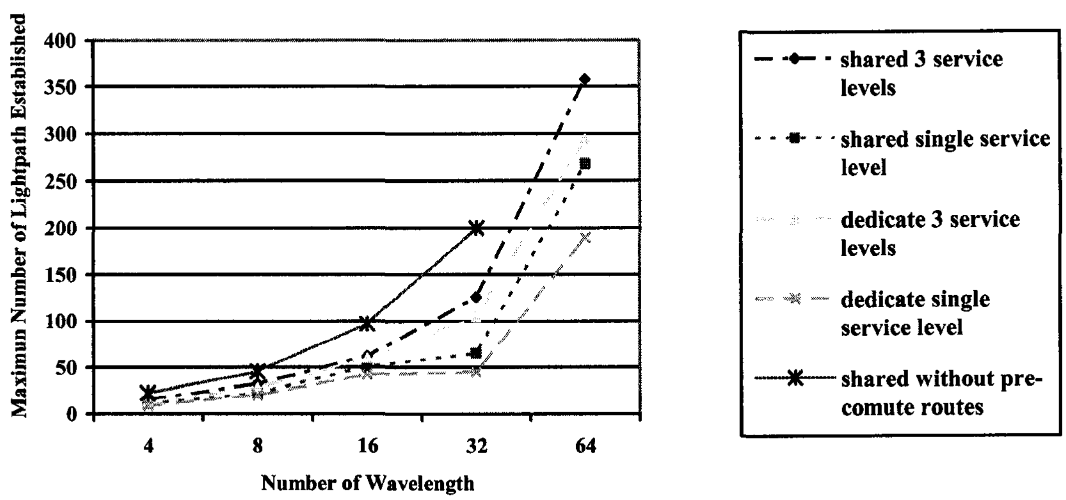


Fig.4.9 No. of connections vs. wavelengths in 53-node network

Results from experiments carried out on all networks show that there is a significant decrease in the number of blocked connections when we introduce multiple levels of service. This is expected, since idle backup resources can be utilized by level 0 connections. Also, as expected, the blocking probability is less for shared path protection scheme than for dedicated path protection. We also see that the shared path protection schemes (both with single and multiple service levels) perform significantly better than the corresponding dedicated path protection schemes. Fig. 4.6 shows the results for the 14-node NSFNET network. In this case, we see that having multiple priority levels allows 40% more connections to be established, than using shared single priority level path protection and 50% more connections, than using dedicated path protection.

All the figures also show that shared path protection without pre-computed route establish more connections than pre-computed 3 alternative routes. This is because pre-computing up to 3 alternative routes limits the search space.

Our experiments clearly show that having multiple service levels improves performance and that shared path protection performs significantly better than dedicated path protection. However, the amount of improvement varies with the size and connectivity of the network.

2) **Solution Time**

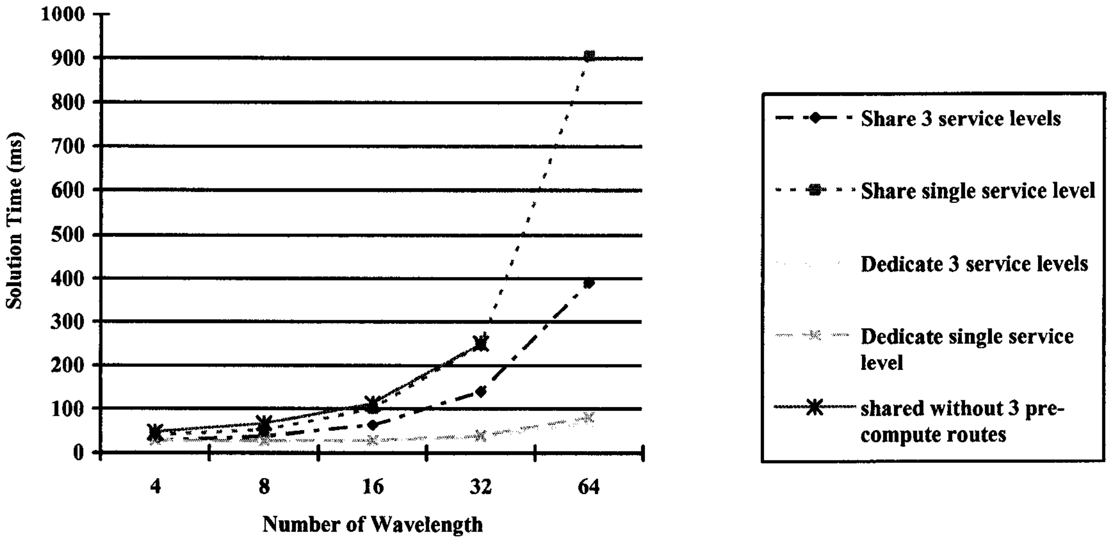


Fig.4.10 Solution time vs. wavelengths in 6-node network

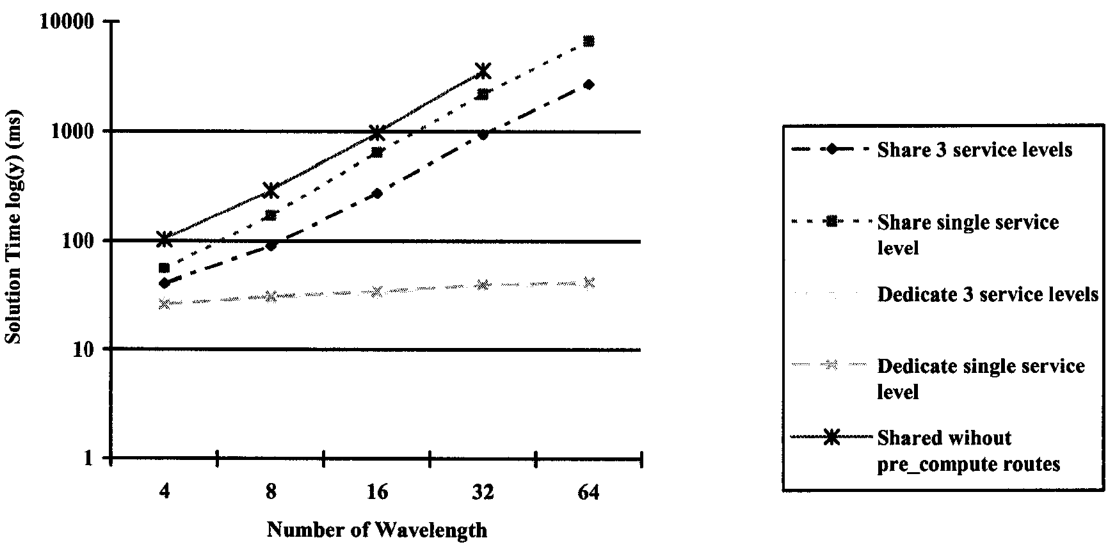


Fig.4.11 Solution time vs. wavelengths in 10-node network

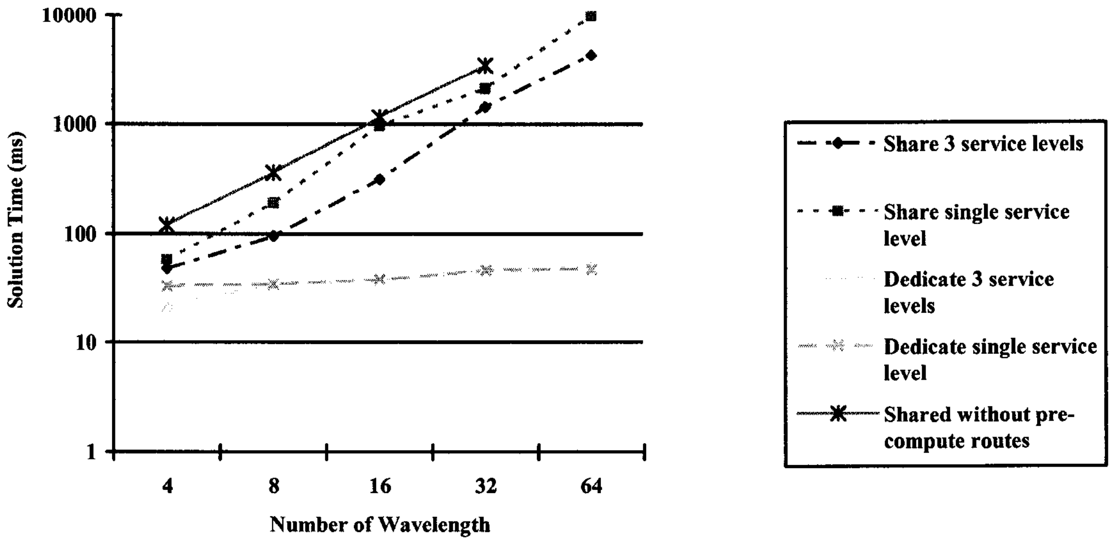


Fig.4.12 Solution time vs. wavelengths in NSFNET

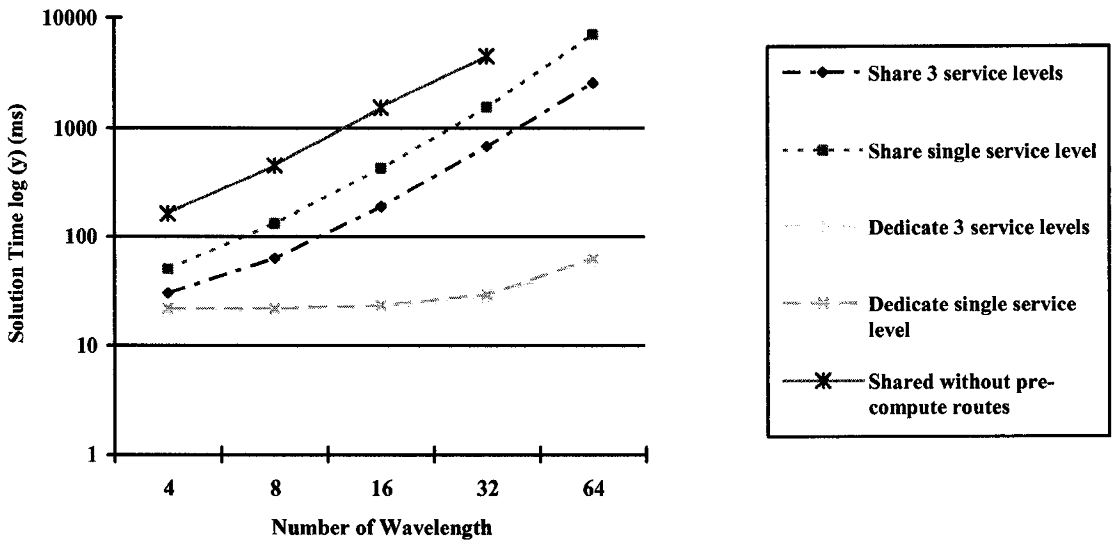


Fig.4.13 Solution time vs. wavelengths in ARPANET

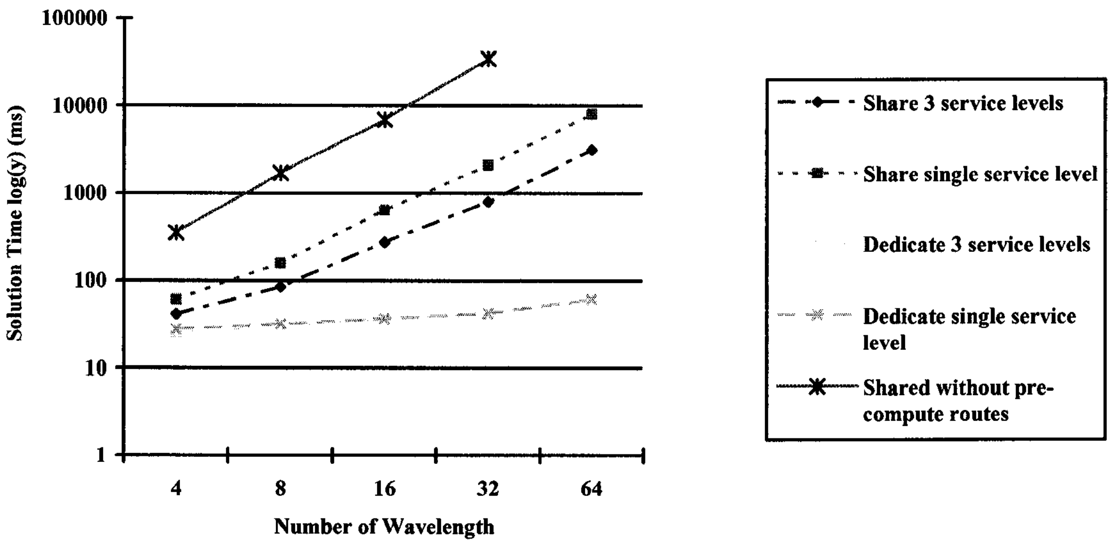


Fig.4.14 Solution time time vs. wavelengths in 30-node network

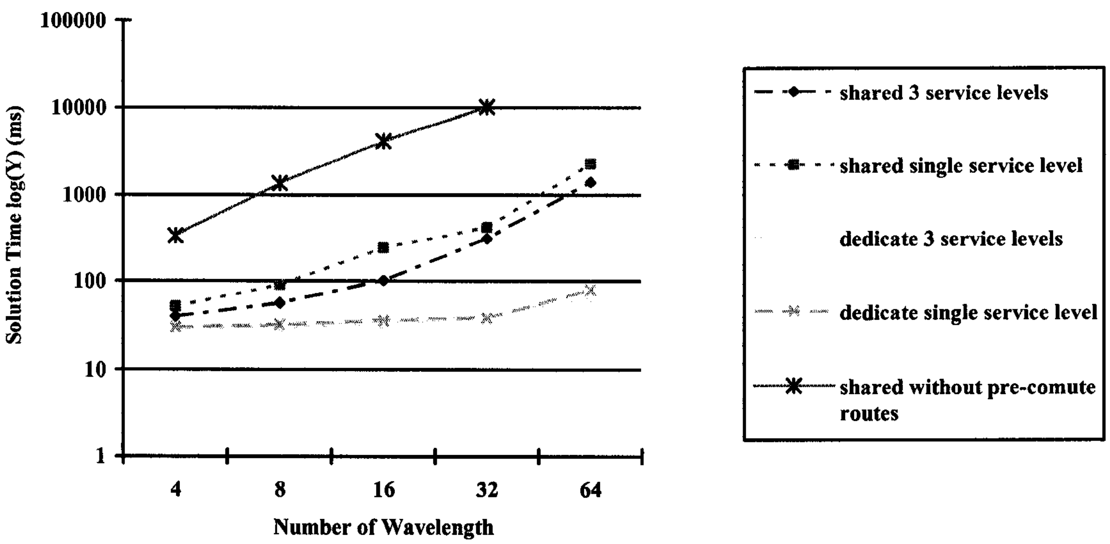


Fig.4.15 Solution time vs. wavelengths in 53-node network

Fig.4.10 – Fig.4.15 show the average solution times for dedicated and shared path protection, for multiple and single level of service, for different networks. Our experiments indicate that the solution time for dedicated path protection is much shorter than that for shared path protection and is also much less sensitive to the problem size. This is expected, since dedicated protection has a much smaller search space. We also see that for a given network the solution time increases with the number of wavelengths, since this increases the number of variables and constraints in the formulation.

Results from experiments carried out on all networks show that by pre-computing 3 alternative routes, the solution time of our shared path protection is much shorter than that of shared without pre-compute routes approach proposed in [Hu03] and is also much less sensitive to the problem size. For example, as showed in Table 4.5, the solution time for 30-node network is 41.2 ms using shared approach with pre-computing 3 routes, 351 ms using shared without pre-compute routes approach when the number of wavelength is 4. It increases to 799 ms and 34500 ms respectively when the number of wavelength increases to 32. It is clear, shared with pre-computing routes approach greatly shortens the solution time, and is especially useful for larger size network.

For a given network, with a specific number of wavelengths, the solution time is always less when we have multiple levels of service. This is because, when we have a single level of service, we assume all connections require level 2 service. Therefore, we *always* have to search for both a primary and backup lightpath. The solution times shown in all solution time vs. wavelengths figures are averaged over all experiments carried out on each network. A more detailed analysis indicates that the solution time varies greatly with the network load and is significantly shorter under low load conditions.

3) Resource Utilization

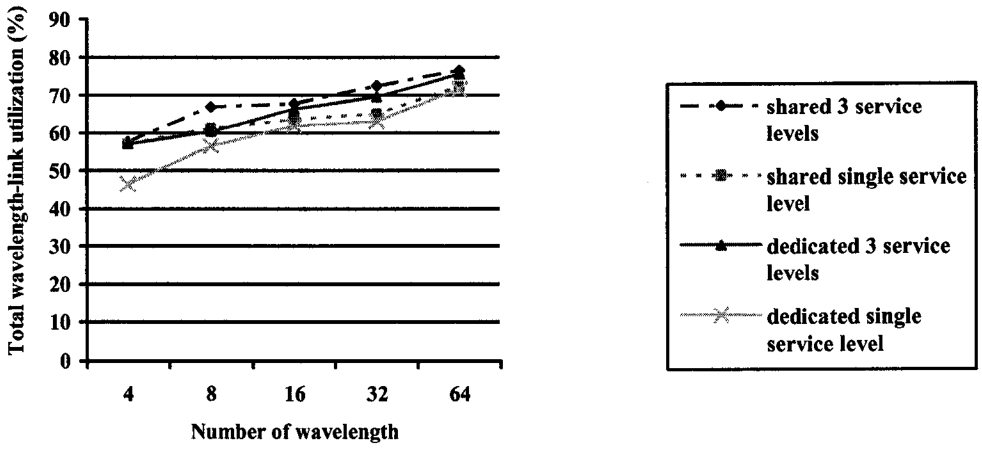


Fig.4.16 Total wavelength-link utilization in 6-node network

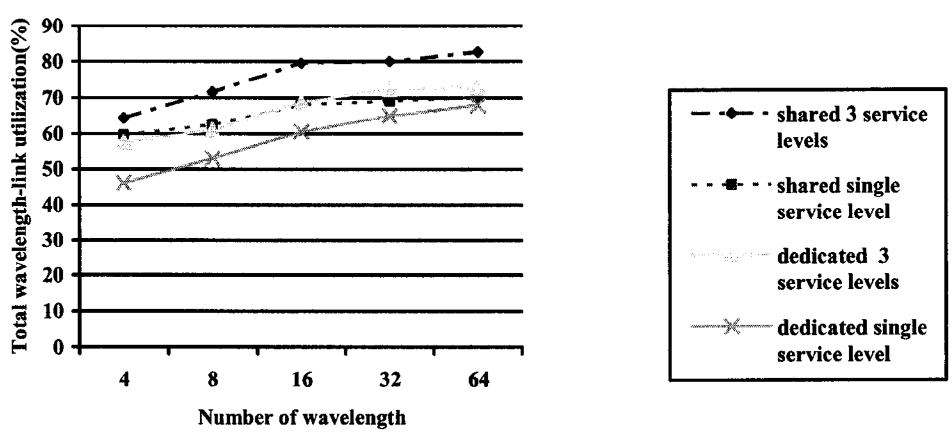


Fig.4.17 Total wavelength-link utilization in 10-node network

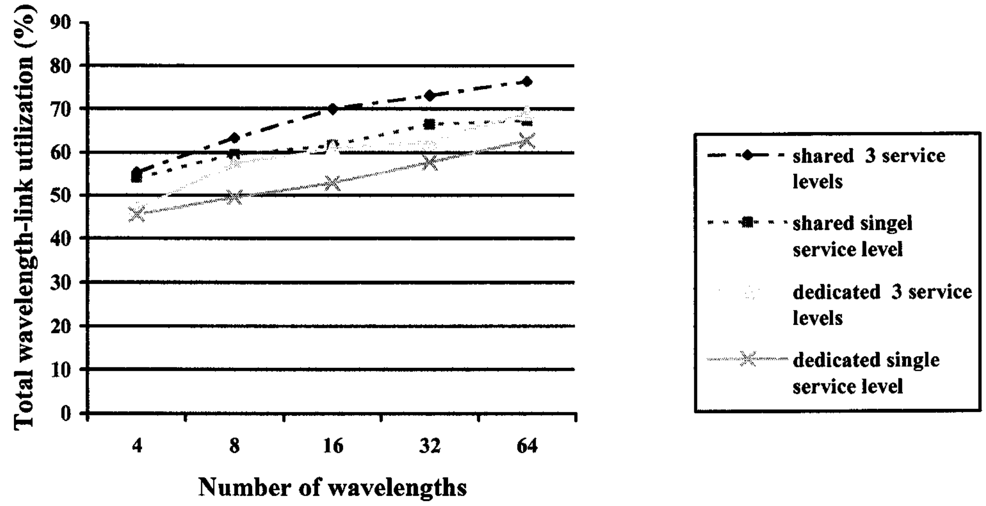


Fig.4.18 Total wavelength-link utilization in14-node NSFNET

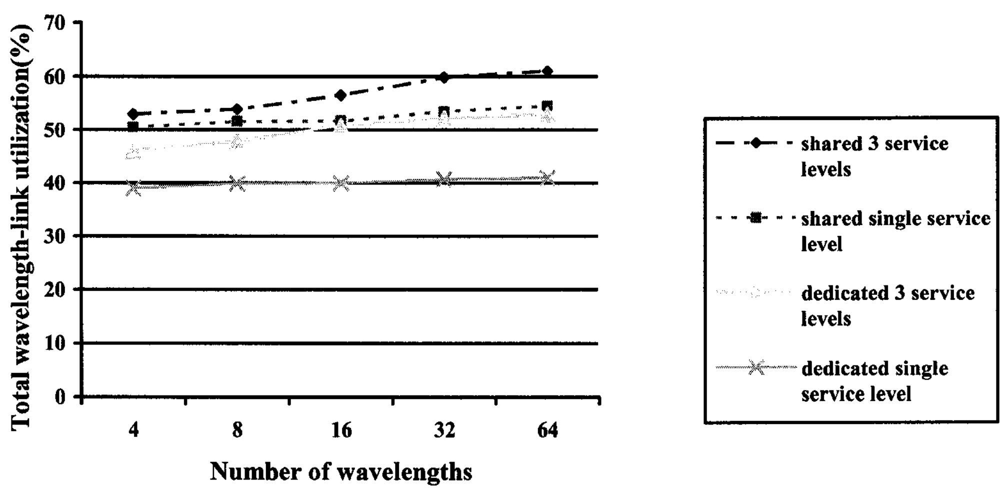


Fig.4.19 Total wavelength-link utilization in20-node ARPANET

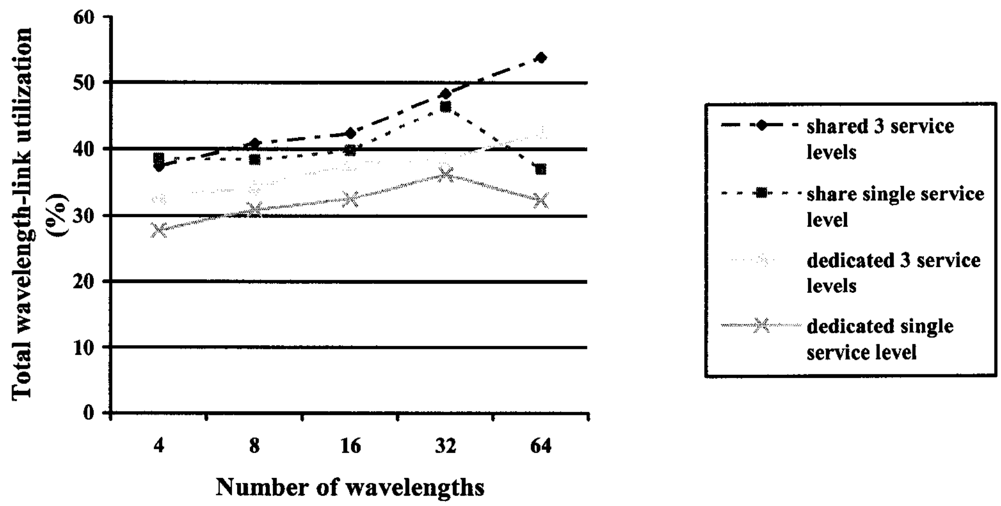


Fig.4.20 Total wavelength-link utilization in 30-node network

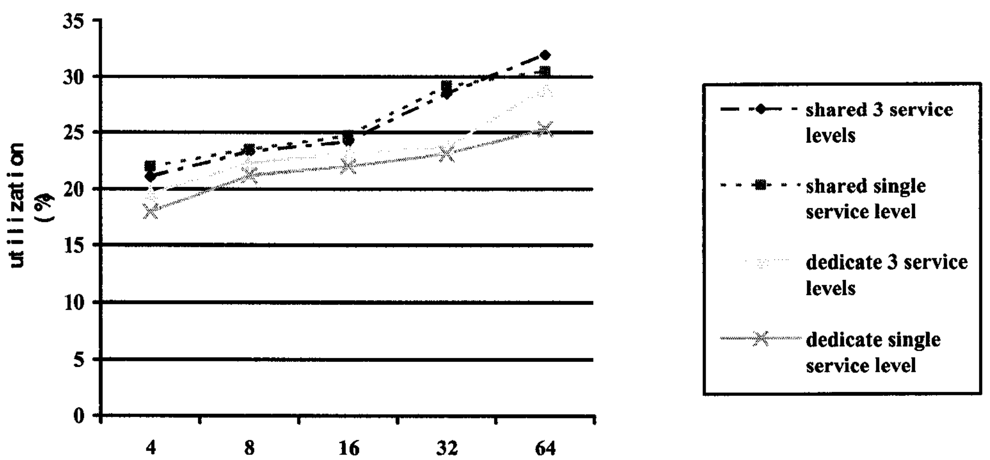


Fig.4.21 Total wavelength-link utilization 53-node network

In order to measure resource utilization, we define two parameters. The *total wavelength-link utilization* is the number of wavelength links allocated to both primary and backup paths, expressed as a percentage of the number of available wavelength links in the network. The *active wavelength-link utilization* is the number of wavelength links actually carrying data (i.e. allocated to primary lightpaths), expressed as a percentage of the number of available wavelength links in the network.

We see from Fig. 4.16 – Fig.4.21 that shared path protection with multiple services levels has higher resource utilization than both dedicated path protection and shared protection with a single service level. From Fig.4.18, we also see that for 64 wavelengths, the utilization for dedicated path protection (with multiple service levels) becomes higher than that for shared path protection (single service level), even though shared path protection accommodates more connections (Fig. 4.6). This demonstrates that our formulation for shared path protection is able to use resources much more efficiently.

In fig.4.20, the total wavelength-link utilization of both shared and dedicated path protection with single service level become lower when the number of wavelength = 64. That is because, when the number of wavelength doubled, the available resources are doubled. However, due to the connectivity of the network, it is not possible to increase the number of connections simply by adding more wavelengths. So, the utilization drops.

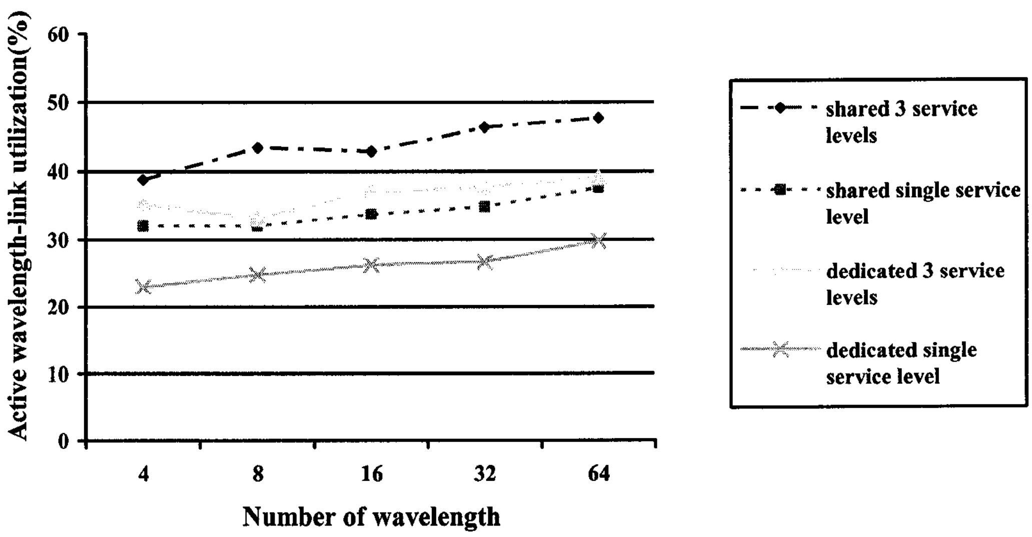


Fig.4.22 Active wavelength-link utilization in 6-nodes network

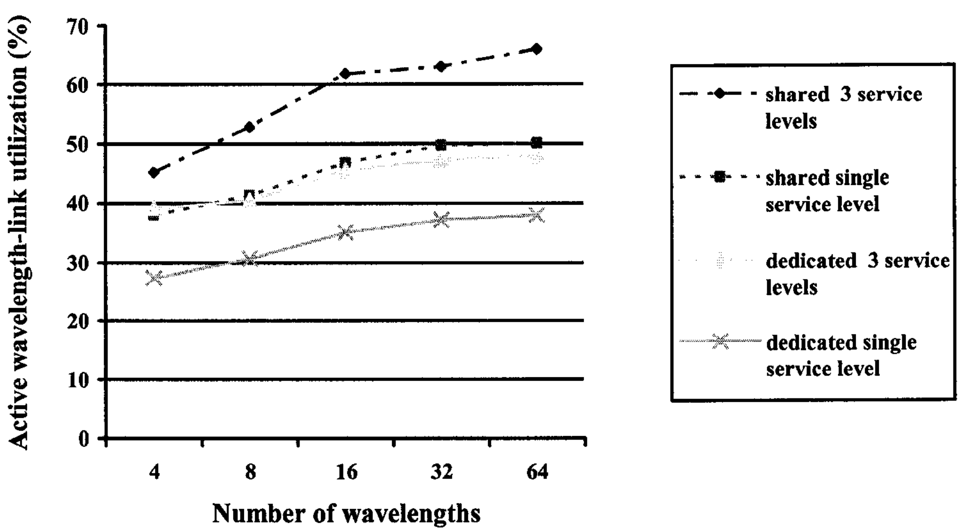


Fig.4.23 Active wavelength-link utilization in 10-node network

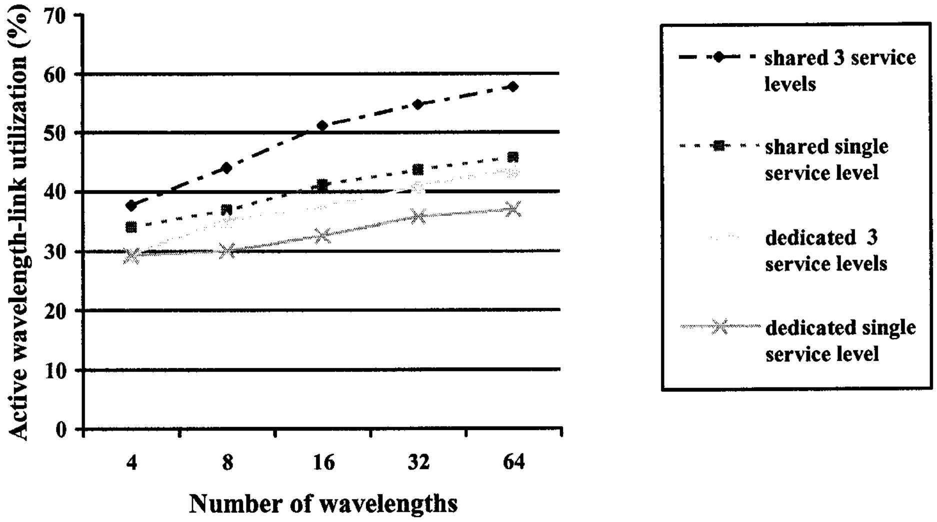


Fig.4.24 Active wavelength-link utilization in14-node NSFNET

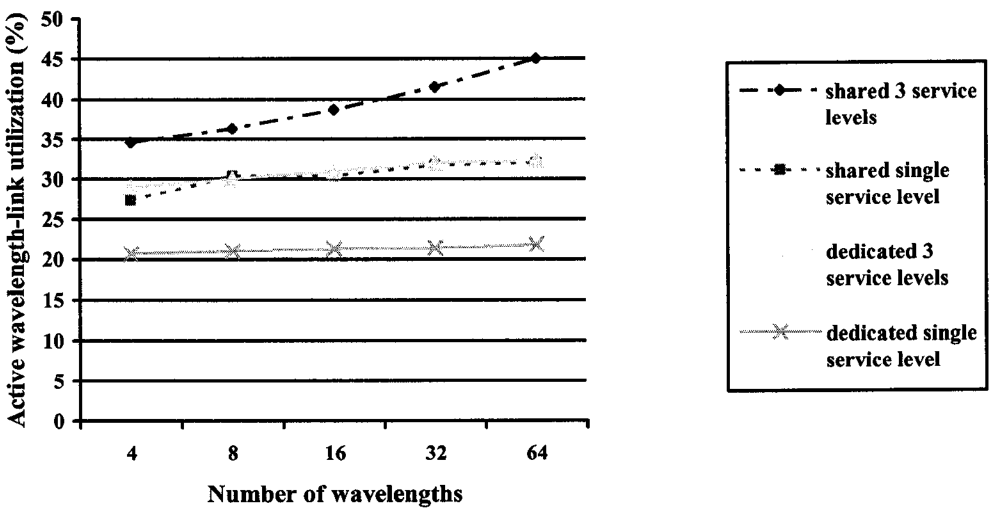


Fig.4.25Active wavelength-link utilization in 20-node ARPANET

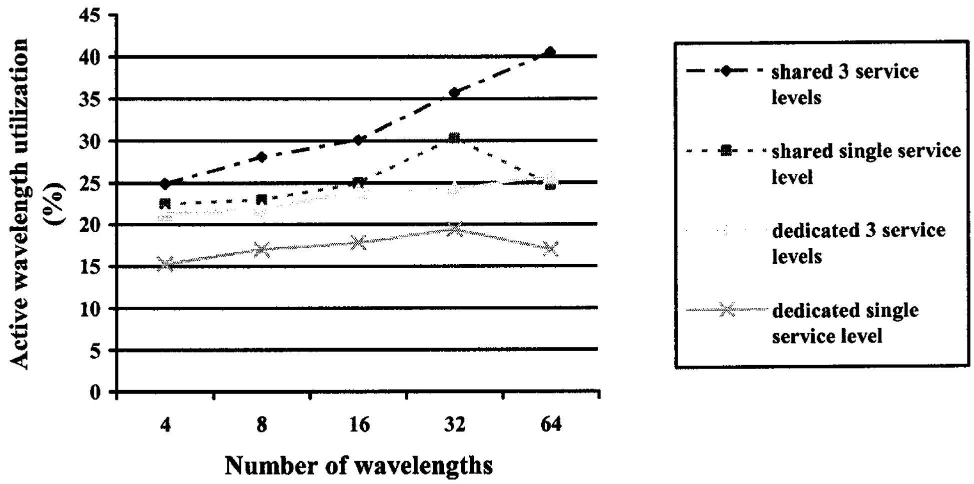


Fig.4.26 Active wavelength-link utilization in 30-node network

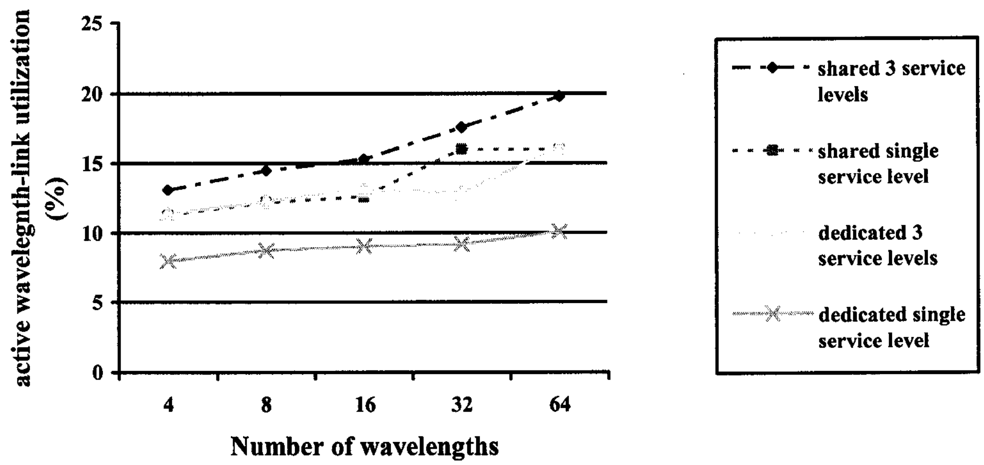


Fig.4.27 Active wavelength-link utilization in 53-node network

Fig. 4.22- Fig.4.27 show the active wavelength-link utilization for the four schemes in each network. In this case, the active wavelength-link utilization of shared path protection with multiple services levels is much higher than that of shared protection with single service level and dedicated schemes. From Fig.4.25, we can see that shared protection with multiple levels of service use active resources more than 50% efficient than other

schemes when the number of wavelength = 64. These results confirm that by introducing multiple priority levels, we can greatly improve resource utilization efficiency over traditional protection schemes.

Chapter 5

Conclusions and Future Work

Wavelength Division Multiplexing (WDM) technology can utilize the huge capacity available in an optical fiber (in the order of terabits per seconds). Optical networks employing WDM technology provide very high data transmission rates, low error rates, and low delay. These networks offer suitable solutions to meet the bandwidth demand arising from several emerging applications such as Internet and web browsing, graphics and visualization, and multimedia conferencing [CP99]. Currently, WDM networks mainly act as long haul backbone networks. The lightpaths in such network are known and setup in advance and do not change frequently. Recent advances in WDM techniques, makes short term leasing of lightpaths, to transmit crucial data possible and this trend is becoming more popular. Dynamic lightpath allocation is necessary in order to satisfy such connection requests.

5.1 Conclusions

In this paper we have presented a new and efficient formulation for dynamic lightpath allocation, using both shared and dedicated path protection. Our formulation can handle multiple levels of service and we have investigated how this affects the performance of the networks. Traditional shared and dedicated path protection schemes (in which all primary lightpaths are required to have a backup path) can be treated simply as a special case of our formulation, where all connections are level 2 connections. Our MILP formulations have three novel features: (1) we introduce different QoS to further improve network resources utilization (2) we pre-computed up to 3 alternative routes to shorten solution time (3) we use as many as possible continuous variables instead of integer variables to simply MILP formulation, so as to shorten solution time. We have carried out extensive experiments on 6 different network including well-known networks: NSFNET and ARPANET and some large networks with more than 30 nodes. The results show that allowing multiple service levels leads to more efficient resource utilization and an increase in the number of connections that can be set up. This is true for both shared and dedicated path protection. We also see that dedicated path protection can provide very quick solutions, but it does not utilize resources as efficiently as shared path protection. Under low load conditions, dedicated path protection will likely provide satisfactory solutions. As network traffic increases, the shared path protection scheme will be able to establish connections, which would otherwise be dropped, if only dedicated protection is used.

We note that for many proposed MILP formulations reported in literature the complexity grows very quickly with network size. The result is that it usually takes several hours (for shared path protection) to obtain an optimal solution for realistic problems [RSM03]. In our formulation, the number of integer variables is significantly less than other formulations. Therefore, the solution times, even for the larger networks, are reasonable and allow us to obtain optimal solutions for practical networks.

5.2 Future work

The work presented in this thesis can be extended in a number of ways. Given below are some possible enhancements.

- Consider wavelength conversion: In this thesis, we consider WDM networks without wavelength conversion. This limits the number of available lightpaths and adds more constraints. A MILP formulation capable of handling wavelength conversion will likely allow more lightpaths to be setup with available resources. Of course, the cost of such networks will be more expensive.
- Use different algorithms to pre-compute alternative routes: We have used Dijkstra's algorithm to pre-compute up to 3 shortest alternative routes for any node pair in this thesis. From our experiments, we found that sometimes, finding shortest route will limit the number of available routes. This, in turn, reduces the maximum number of connections that can be established. This is the case with the 30 and 53 node networks in section 4.2.3. Different algorithms for pre-computing alternative routes can be tried.

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Appendix A: Glossary

ARPANET – Advanced Research Projects Agency Network

CPLEX – C Programming Language + simplex

ILP – Integer Linear Programming

ITU-T – International telecommunications Union on Telecommunications

LP – Linear Programming

MILP – Mixed Integer Linear Programming

NSFNET – National Science Foundation Network

OXC – Optical Cross-Connect

RWA – Routing & Wavelength Assignment

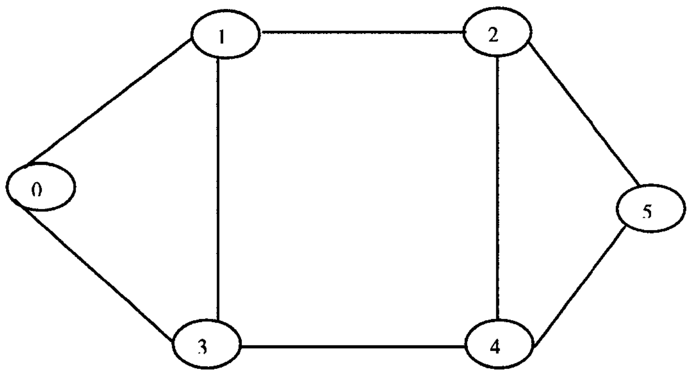
SDH – Synchronous Digital Hierarchy

SONET – Synchronous Optical Network

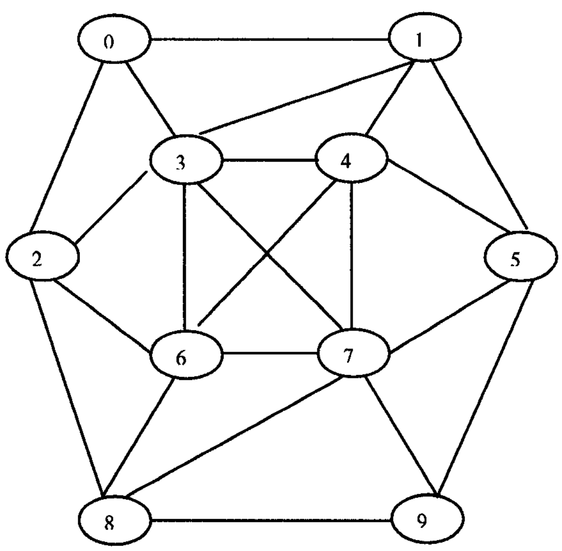
WDM – Wavelength Division Multiplexing

Appendix B: Topology of Testing Networks

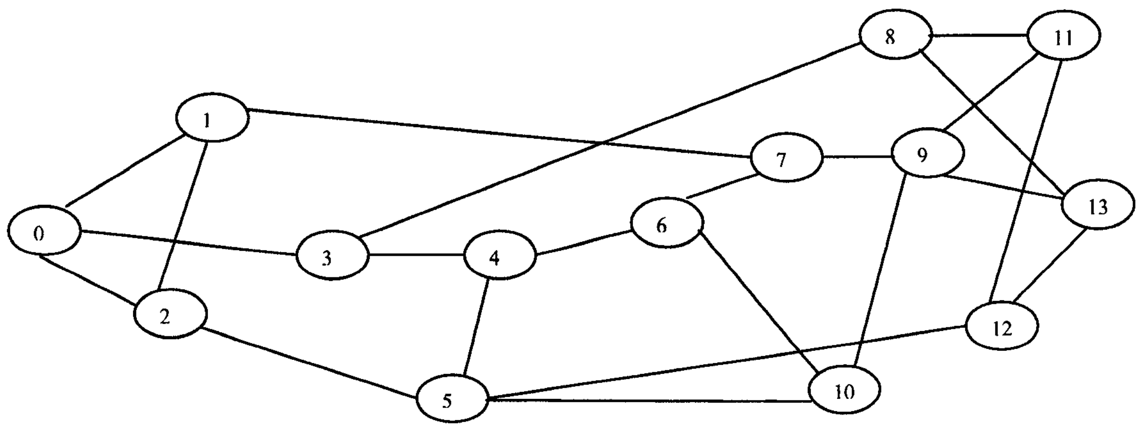
1.Topology of network1- 6 nodes, 8 edges



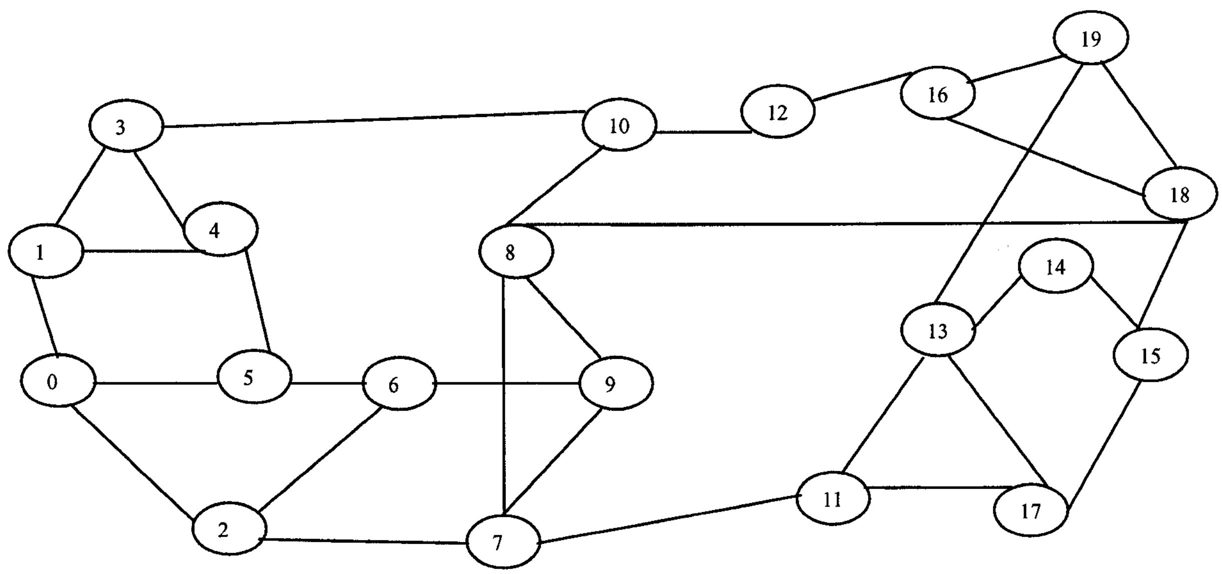
2.Topology of network2- 10 nodes, 22 edges



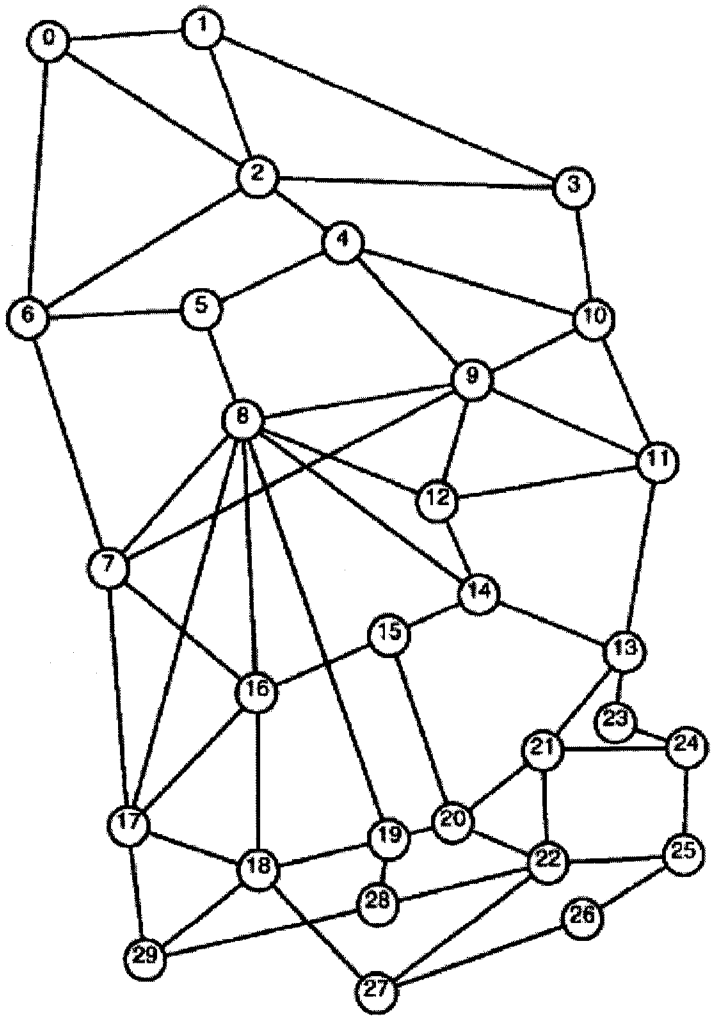
3. Topology of NSFNET- 14 nodes, 21 edges



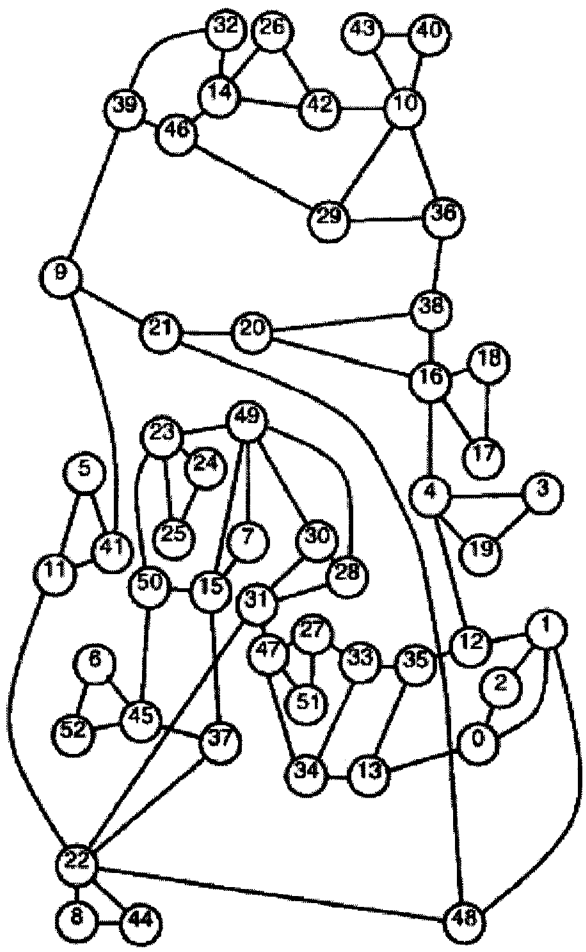
4. Topology of ARPANET- 20 nodes, 31 edges



5. Topology of testing network3 [IMG98] – 30 nodes, 59 edges



6. Topology of testing network4 [IMG98] – 53 nodes, 80 edges



VITA AUCTORIS

Name:	Suqin Zhong
Place of Birth:	Nanjing, China
Year of Birth:	1969
Education:	HoHai University Nanjing, China 1987-1991 B.Sc in Computer Science
	HoHai University Nanjing, China 1993-1995 Master in Economics
	University of Windsor Windsor, Ontario, Canada 2001-2004 M.Sc in Computer Science