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Capacity optimization for surviving double-link failures in mesh-restorable optical networks

by

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ABSTRACT

Network survivability is a crucial requirement in high-speed optical networks. Most research to date has been focused on the failure of a single component such as a link or a node. A double-link failures model in which any two links in the network may fail in an arbitrary order was proposed recently in literature. Three loop-back methods of recovering from double-link failures were also presented. The basic idea behind these methods is to pre-compute two backup paths for each link on the primary paths and reserve resources on these paths. Compared to protection methods for single-link failure model, the protection methods for double-link failure model require much more spare capacity. Reserving dedicated resources on every backup path at the time of establishing primary path itself would reserve excessive resources. In this thesis, we capture the surviving double link failures in WDM optical networks as a single Integer Linear Programming (ILP) based optimization problem. We use the double-link failures recovery method available in literature, develop rules to identify the scenarios where the backup capacity among intersecting demand sets can be shared. We employ the backup multiplexing technique and use ILP to optimize the capacity requirement while providing 100% protection for double-link failures. The numerical results indicate that, for the given example network and randomly picked demand matrix, the shared-link protection scheme that uses backup multiplexing provides 10-15% saving in capacity utilization over the dedicated-link protection scheme that reserves dedicated capacity on two backup paths for each link. The main contribution of this thesis is that we

provide a way of adapting the heuristic based double-link failure recovery method into a mathematical framework, and use technique to improve wavelength utilization for optimal capacity usage.

1 INTRODUCTION

1.1 Survivability in WDM optical network

An explosion in the growth of web-related services offered over the Internet is creating a growing demand for bandwidth. Recent reports indicate that the Internet is growing faster than ever, with traffic across the core of the network quadrupling over the last year [1]. The challenge is to react quickly to these increasing bandwidth requirements while maintaining reliable service. The networks should be designed and operated so as to provide adequate capacity in geographical areas where demand is growing fastest, without over-provisioning to the point of compromising network revenue. All-optical networks employing dense wavelength division multiplexing (DWDM) have fundamentally changed the economics of transport networking, as they can effectively satisfy the growing demand for bandwidth. In WDM networks, the huge bandwidth available on an optical fiber is divided into multiple channels. Each channel can carry bandwidth up to several gigabits per second. Researchers have demonstrated error-free transmission of 1 terabit per second using 100 WDM 10-Gb/s channels with 50 or 100-GHz channel spacing [2]. There are 40-channel DWDM systems commercially available [3], which can be upgraded to 96 channels, incrementally, on a channel-by-channel basis. A minimum unit of resource allocation is an optical channel, which consists of a route and a wavelength assigned on each link along the route. A WDM optical network consists of a set of wavelength cross-connects (WXCs) interconnected by point-to-point fiber links in an arbitrary topology. A wavelength-selective cross-connect (WSXC) is capable of optically switching an optical signal from an incoming fiber to an outgoing fiber on the same wavelength. WDM networks that use WSXC are referred to as wavelength-selective networks. Unlike a WSXC, a wavelength–interchange cross-connect (WISC) is capable of changing the wavelength of an incoming signal by using wavelength converters. If wavelength translation is performed in optical switching, then each channel may be assigned different wavelengths on each link along the route; otherwise the same wavelength has to be assigned on all links along the route. In this thesis, we assume that there is no wavelength translation in the network.

A connection request is satisfied by establishing a lightpath from the source node of the connection to the destination node. A light path is an all-optical channel that may span multiple fiber links, to provide a circuit –switched inter-connection between two nodes. In the absence of wavelength converters, a lightpath would occupy the same wavelength on all fiber links that it traverses.

Recent times have witnessed significant shifts in traffic patterns. Major carriers in the United States announced that data traffic, for the first time, has overtaken voice traffic. Many of today's businesses rely heavily on a reliable and continuously available high-speed communications infrastructure. WDM networks are prone to component failures. With millions of wavelength-miles laid out in typical global and nation wide networks, fiber optic cables are among the most prone to failures. TEN (formerly Hermes Europe Railtel), a pan-European carriers' carrier network, estimates an average of one cable cut every four days on their network [4]. When a link fails, all its constituent fibers will fail. A node failure may be caused due to the failure of its associated WXC. A fiber may fail due to its end components. Failure detection, correction and root cause analysis is a difficult problem in WDM optical networks [5]. Since WDM optical networks carry high volume of traffic, it is imperative to design survivable networks to avoid catastrophic socio-economic effects. The survivability refers to the ability of the networks to reconfigure and reestablish communication upon failure, i.e. reestablishing the communication through a lightpath between the end nodes of a failed lightpath.

Many factors make it attractive to carry fast growing IP traffic directly over an optical network without the intervening SONET/SDH layer. In such cases, the entire network needs a new restoration strategy. SONET has its own protection schemes providing fast recovery (of the order of milliseconds). Restoration at the optical layer has several advantages like faster recovery mechanisms, better utilization of resources such as wavelengths and protection for higher layer protocols that do not have their own recovery mechanisms. The key-enabling element in the optical layer is the design restoration strategies that provide sub-second restoration for mesh based optical networks.

1.2 Objective

Most research to date has been focused on the failure of a single component such as a link or a node. A double-link failure model in which any two links in the network may fail in an arbitrary order was proposed recently in literature [6]. Three loop-back methods of recovering from double-link failures were also presented. The basic idea behind these methods is to pre-compute two backup paths for each link on the primary paths and reserve resources on these paths. Compared to protection methods for single-link failure model, the protection methods for double-link failure model require much more spare capacity. Reserving dedicated resources on every backup path at the time of establishing primary path itself would reserve excessive resources. In this thesis, we use the double-link failures recovery method in the literature, and develop the backup multiplexing technique to share the backup capacity whenever it is possible. We use Integer Linear Programming to optimize capacity utilization and provide 100% protection guarantee for double-link failure recovery.

1.3 Thesis outline

The remainder of thesis is organized as follows. Chapter 2 reviews prior work on survivable optical networks. Chapter 3 details the double-link restoration model and three link-based recovering methods in the literature. In chapter 4, we develop the rules for backup multiplexing in double-link failures model. Chapter 5 presents the ILP formulation for capacity optimization for both dedicated- and shared-link protection schemes. Chapter 6 provides results to demonstrate the improvements obtained in capacity utilization by optimal wavelength sharing over the dedicated protection case. Chapter 7 presents our conclusions.

2 LITERATURE REVIEW

2.1 Classification of single-link failure recovery methods

The methods for surviving single-link failure can be broadly classified into protection-based and restoration-based [7] [8], as shown in Fig 1[9]. Protection-based methods identify a backup path and reserve resources on backup path at the time of establishing primary path. In contrast, the dynamic-restoration-based methods discover the resources for restoration at run time. Generally, restoration-based methods are more efficient in utilizing capacity and provide resilience against different kinds of failures, while protection-based methods have the advantage of fast restoration and providing guarantees on the restoration ability.

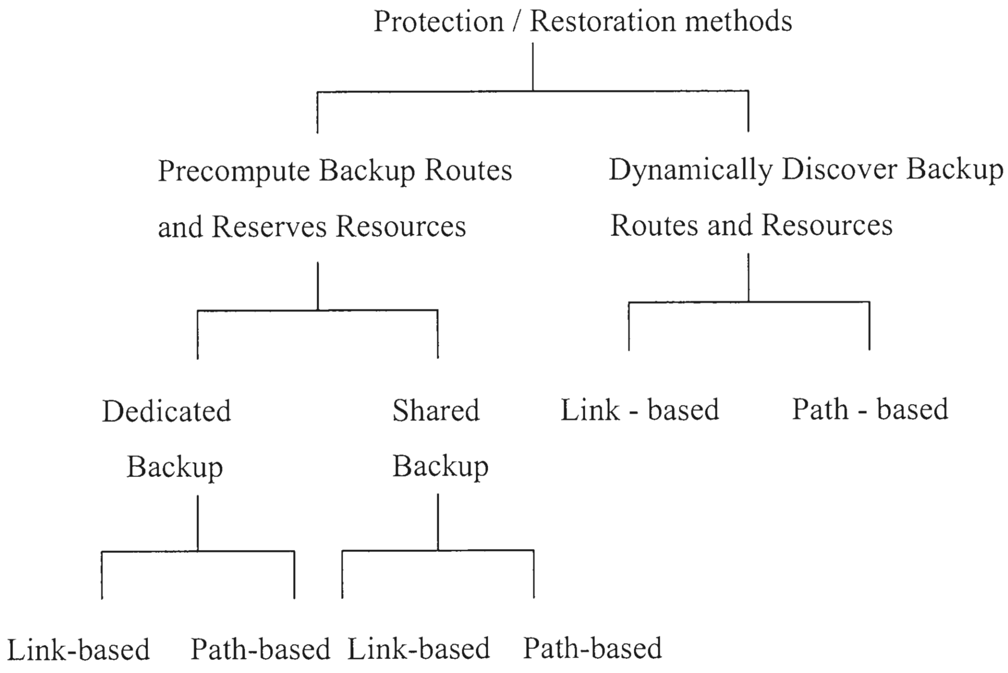


Figure 1 Different methods for surviving single-link failures

A protection-based or restoration-based method is either link-based or path-based. A link-based method employs local detouring while a path-based method employs end-to-end detouring. A link-based method reroutes traffic around the failed component. When a link fails, a new path is selected between the end nodes of the failed link. The portion of working lightpath excluding the failed link remains same. In case of wavelength- selective networks, the backup path must necessarily use the same wavelength as that of primary path as its working segment is retained. In a path-based restoration method, a backup lightpath is selected between the end nodes of the failed primary lightpath. Fig 2 illustrates the difference between the path-based and link-based methods.

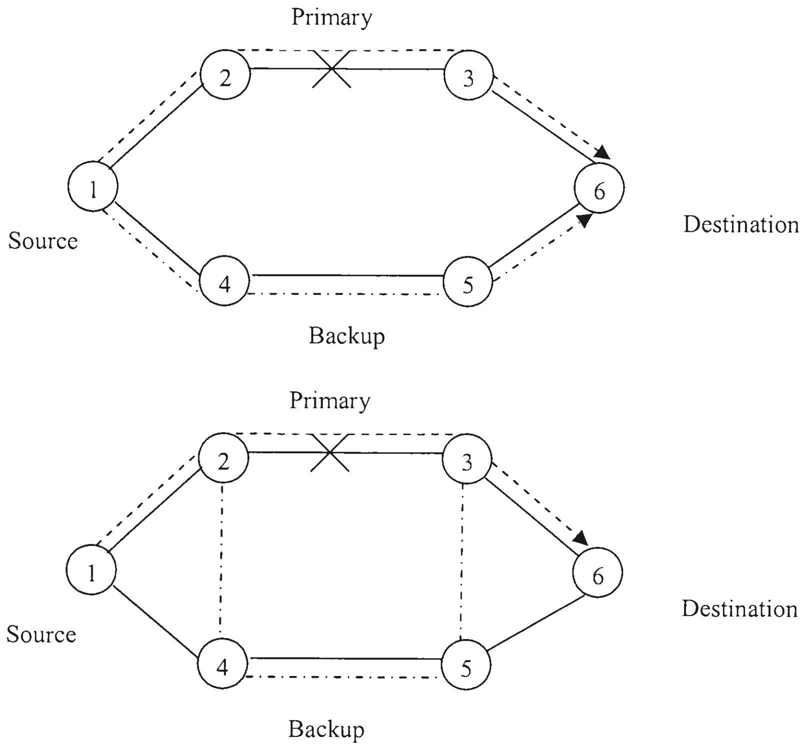


Figure 2 The difference between the path-based and link-based methods

A connection is established on path 1->2->3->6. Upon failure of link 2->3, path-based methods reroutes the traffic on 1->2->3->6 to 1->4->5->6, while link-base method reroute the traffic on 2->3 to 2->4->5->3. Therefore, in the case of link-based method, the original traffic on 1->2->3->6 is on 1->2->4->5->3->6 after rerouting. The path-based methods have better resources utilization, while the link-based methods requires less signaling and have shorter restoration time.

In Protection-based methods, the resources reserved can be either dedicated for each failure scenario or shared among different failure scenarios. The dedicated reservation method has an advantage of shorter restoration time, as WXCs are configured for the back up path at the time of establishing primary path. However, this method reserves excessive resources. For better resource utilization, multiplexing techniques can be employed. In single-link failure model, only one link can fail at any time. If two primary lightpaths do not fail simultaneously, their backup paths can share a wavelength channel. This technique is known as *backup multiplexing*.

The following summarize the different schemes for surviving single –link failure [9].

1.) **Dedicated-link-protection**: During the call setup, a backup path and wavelength are reserved around each link of primary path. A reserved wavelength is dedicated to the connection. Upon failure of a link, the connections that traverse the link are rerouted to the backup path, which is from one end of the failed link to another end of the failed link.

2.) **Shared-link-protection**: similar to the dedicated-link-protection except that the reserved wavelengths on the links of the backup path may be shared with other backup paths.

3.) **Dedicated-path-protection**: at the time of call setup for each primary path, a link-disjoint backup path and wavelength are reserved and dedicated to that call. Upon failure of a link, the connections that traverse the link are rerouted to the corresponding backup paths, each of which is from the source node to the destination node of the corresponding primary path.

4) **Shared-path-protection**: similar to dedicated-path-protection except that the backup wavelength reserved on the links of backup path may be shared with other backup paths. 5)

5) **Link-restoration**: The end-nodes of the failed link participate in a distributed algorithm to dynamically discover a route around the link, for each wavelength that traverses the link. If no new route (and associated wavelength) is available, that connection is blocked.

6) **Path-restoration**: The source and destination nodes of each connection traversing the failed link participate in a distributed algorithm to dynamically discover a backup route on an end-to-end basis. If no new route (and associated wavelength) is available, that connection is blocked.

2.2 Related work

Survivability in mesh-based network has been studied extensively. In [10] [11], the various operational phases in survivable WDM networks were captured as a single ILP problem. The framework also captured service disruption aspects. In [9], ILP formulations have been developed for three different protection based methods: dedicated-path protection, shared-path protection (backup multiplexing) and shared-link protection (backup multiplexing). The objective is to minimize the number of wavelengths in a single-fiber wavelength –selective network. A distributed control protocol for dynamic-restoration-based methods has been proposed in [12]. Upon a link failure, this protocol searches for backup lightpaths for the failed lightpaths. Both the link-based and path-based restorations have been considered. In [13], the problems of designing the restoration network for a given set of demands for wavelength –convertible networks have been considered. The problem has been formulated as an integer programming problem. The objective function is to minimize the weighted number of wavelength required. The links are weighted by capacity consumption per wavelength. The failure-independent path-based restoration is used.

A ring-like protection approach by embedding cycles on a given mesh topology was proposed in [14] [15]. The network is assumed to be 2-edge connected and is represented by a directed graph (digraph). The links of the digraph are coved by two directed cycles such that each link is covered by a cycle in each direction exactly once. Then, all the working fibers on a link can backed up by the protection fibers on the cycle that does not include the link. The advantages of this technique are protection switches can be pre-configured, and no signaling is required. The disadvantages include no guarantee recovery for non-planar graph and requiring wavelength conversion. Two variations to the above method were presented in [16] [17]. These methods are applicable to planar graph as well.

Besides the recent work in [6], there has been some research in surviving two-link failures [18] [19] [20]. Spare-channel design schemes for a self-healing network in the case of double link failures were discussed and the problem was solved using linear programming method in [18]. A hierarchical classification scheme for two-link failures in all optical networks was presented in [19]. The associated aspects of the recovery algorithms designed for each class were identified and an algorithm's ability to recover from each class failures was measured using vulnerability. In [20], the two-link failures restorability of mesh networks that are efficiently designed to fully restore any single link failure was studied by experimental computational approach. The capacity cost of strictly designing for 100% two-link failures restorability was determined by optimization formulations.

3. DOUBLE-LINK FAILURES RECOVERY MODEL

Most research to date has considered the failure of a single component such as a link or a node. It is possible to have two links fail simultaneously. Two reasons were given in [6] to motivate the need for considering double-link failures. Normally, recovery from the failure of a link is completed within a few milliseconds to a few seconds. However, it may take a few hours to a few days to repair the failed physical link. It is certainly conceivable that a second link fails in this duration, thus causing two links to be down at one time. Another reason is that two links may be physically routed together for some distance in real situations. A single backhoe accident may lead to the failure of both links.

Three link-based double-link failure recovery methods were also presented in [6]. For the graph to remain connected after any two edges fail, the graph must be 3-connected. By Menger's theorem [21], a graph is k-connected if and only if there exists k-disjoint paths between every pair of nodes in the graph. These recovery methods assume the graph is 3-connected, and the second link fails after the first failure is completed. These methods also work when two links fail simultaneously. We review the three methods in the following section.

3.1 Backup paths with link identification – method I and method II

Two edge-disjoint paths, a first backup path $b_1(e)$ and a second backup paths $b_2(e)$ are pre-computed for each edge e. when e fails, the first backup path $b_1(e)$ is used for rerouting.

At the same time, all nodes in the network are informed of the failure through signaling. Suppose second link *f* fails at this point. This failure is notified to all nodes as before. There are four possible cases:

i) $b_1(f)$ does not use *e*, *f* does not lie on $b_1(e)$

In this case, $b_1(e)$ will continue to be used to reroute the traffic on *e*, and $b_1(f)$ will be used to reroute the traffic on *f*.

ii) $b_1(f)$ uses *e*, *f* does not lie on $b_1(e)$

In this case, $b_1(e)$ will be continue to be used reroute the traffic on *e*. $b_1(f)$ cannot be used because link *e* is still down. $b_2(f)$ will be used to reroute the traffic on *f*.

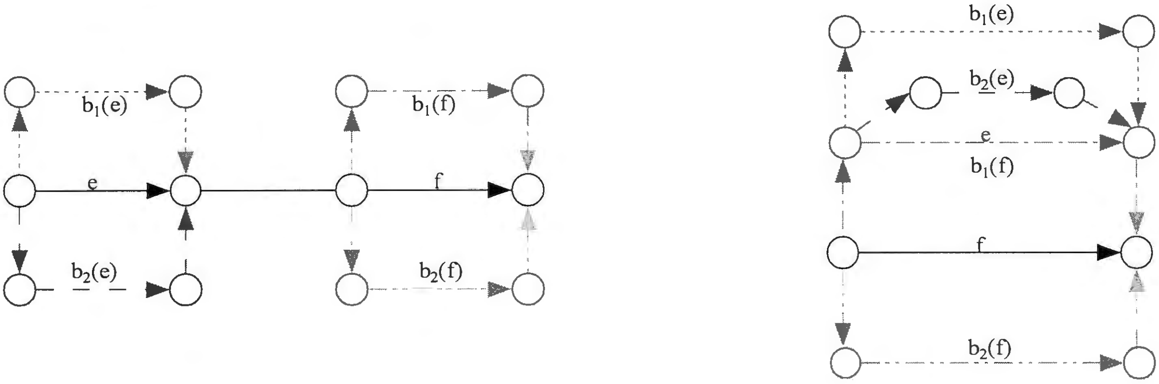
iii) $b_1(f)$ uses *e*, *f* lies on $b_1(e)$

In this case, $b_1(e)$ and $b_1(f)$ both cannot be used as restoration routes. Recovery method I and II reroute the working traffics on primary links *e* and *f* in different ways. In Method I, when f fails, $b_2(f)$ will be used to reroute the working traffic on *f*. when the information about *f*'s failure reaches the end-nodes of *e*, these nodes switch the working traffic originally on e from $b_1(e)$ to $b_2(e)$. Knowledge of which links lie on a backup path is necessary to carry out this process. In Method 2, $b_2(f)$ will be used to reroute both the working traffic on *f* as well as the backup traffic rerouted on $b_1(e)$. Thus, the traffic originally routed on e is now on $(b_1(e)-f) \cap b_2(f)$.

iv) $b_1(f)$ does not use *e*, *f* lies on $b_1(e)$

Similar to case iii, method I and II reroutes the traffic differently. In method I, $b_2(e)$ and $b_2(f)$ will be used to reroute the working traffic on *e* and *f* respectively. In method II, $(b_1(e) - f) \cap b_1(f)$ will be used to reroute the working traffic on e, while $b_1(f)$ will also be used to reroute the working traffic originally on *f*.

The examples of these four cases are shown in Fig 3.



Case i

Case ii

Case iii

Case iv

Figure 3. The examples of four cases of relationship between link *e* and *f*

3.2 Backup paths without link identification – method III

In this method, a single backup path *b (e)* is precomputed for each link. Suppose that for every link $f \in b\ (e)$, a backup path *b (f)* that does not contain *e* can be found. Suppose *e* fails first, and then *f* fails. The working traffic on *f* and rerouted traffic on *f* (in this case, the rerouted traffic from *(e)* are both rerouted to *b (f)* from *f*. Since *b (f)* does not use *e*, this rerouting would be successful. One advantage of this method is that no signaling is necessary to inform the network nodes of a link’s failure. The failure of a link needs only be detected at the end-nodes of that link. The cost for this is that the rerouted traffic when two links fail my have to traverse many links.

Computing such kind of backup path is not a trivial work. A heuristic algorithm was given in [6] to compute the backup paths. It works by contracting the graph G according to a set of rules, computing backup paths for the links in the contracted graph, and then mapping these backup paths to the original graph.

4. BACKUP MULTIPLEXING IN DOUBLE-LINK FAILURES MODEL

The methods for protecting against all possible double-link failures require more backup capacity than the methods for protecting against single-link failure. Thus the efficient utilization of backup capacity is more important. Since the method III computes the backup paths by a sophisticated heuristic algorithm, and method II is similar to method I, we focus only on method I. As we have seen, in method I, two backup paths are precomputed and the resources are reserved on these paths at the time of establishing the primary path. An important observation is that some of backup paths may not be used simultaneously to reroute the traffic on primary paths at any time when any two links fail. These backup paths can share the wavelength channel on common links without violation of 100% restoration guarantee. Suppose e and f are two links randomly picked from the network. We use case i in section 3.1 to illustrate it. Without losing generality, we assume e fails first if e and f are down at the same time. There are following possible failure scenarios related to e or f:

1. e fails first, then f fails. $b_1(e)$ and $b_1(f)$ will be used as backup paths to reroute the traffic on e and f respectively.
2. e fails first, then one of links on $b_1(e)$ $g \in b_1(e)$ fails. When the information of g's failure reaches the end nodes of e, the rerouted traffic on $b_1(e)$ will be switched to $b_2(e)$. f cannot fail during this period because no more than two links can be down at the same time.

3. f fails first, then one of links on $b_1(f)$ $g \in b_1(f)$ fails . This is a scenario similar to the above one. $b_2(f)$ will be used to reroute the working traffic originally on f.
4. e fails first, then a link which is not f and not on either of the two backup paths of e fails. $b_1(e)$ will be used to reroute the traffic on e. The working traffic on second failed link will be rerouted on one of its backup paths.
5. f fails first, then a link which is not e and not on either of the two backup paths of f fails. Similar to rerouting rule in (4), $b_1(f)$ will be used to reroute the working traffic on f, and the traffic on the second failed link will be rerouted to one of its backup paths.

Only $b_1(e)$ and $b_1(f)$ are used simultaneously in the scenario1. Other path pairs $b_1(e)$ and $b_2(f)$, $b_2(e)$ and $b_1(f)$, $b_2(e)$ and $b_2(f)$ are not used simultaneously at any time. If one of above pairs of paths have a common link, they can share the reversed backup wavelengths on this link.

Similar rules of sharing backup wavelengths on common links can be obtained for the cases ii, iii, iv in section 3.1 as well. They are summarized as following. Suppose that e and f are two links in the network. For every link g, two backup paths $b_1(g)$ and $b_2(f)$ are precomputed. Let (i, j) represents the pair of backup paths $b_i(e)$ and $b_j(f)$, $i = 1, 2$, and $j = 1, 2$. There are four pairs of paths that can potentially share backup wavelength on their common links. They are $(1,1)$, $(1,2)$, $(2,1)$, $(2,2)$. Let b_i (e) and $b_{i'}$ (e) represent the two backup paths of link e, i.e. if $i = 1$, then $i' = 2$; if $i = 2$, then $i' = 1$. Similarly, b_j (f) and $b_{j'}$ (f) represent the two backup paths of f.

Rule1: if $e \notin b_j(f)$, $f \notin b_i(e)$, then the pair (1,1) cannot share backup wavelengths on their common links. The other pairs (1,2), (2,1), (2,2) can share backup wavelengths on their common links.

Rule2: if $e \in b_k(f)$, $k = 1$ or 2, $f \notin b_i(e)$, then $(1, k')$ cannot share backup wavelengths on their common links. Pairs $(2, k')$, $(1, k)$, $(2, k)$ can share backup wavelengths.

Rule3: if $e \notin b_j(f)$, $f \in b_k(e)$, $k = 1$ or 2, then $(k', 1)$ cannot share backup wavelengths. Other pairs $(k, 1)$, $(k, 2)$, $(k', 2)$ can share backup wavelengths.

Rule4: if $e \in b_m(f)$, $f \in b_k(e)$, $m = 1$ or 2, $k = 1$ or 2, then (k', m') cannot share backup wavelengths. Other pairs (k, m), (k', m), (k, m') can share backup wavelengths.

5. PROBLEM FORMULATION

In this chapter, we develop the ILP formulation of shared-link protection scheme and dedicated-link protection scheme to optimize the capacity utilization. In shared-link protection, the backup paths can share wavelengths on their common links, while in dedicated-link protection the backup paths cannot.

The following information is assumed to be given: network topology and a demand matrix consisting of the connections to be established. We assume that three alternate routes, which are node and link-disjoint, for each node pair, and two alternate routes, which are also node and link disjoint, for each link, are precomputed. Each route between s-d pair is viewed as W wavelength continuous paths (lightpaths), one path corresponding to one wavelength and therefore, we do not have an explicit constraint for wavelength continuity. There are two ways to measure the capacity efficiency [12]: (a) given a certain capacity, maximize the protected carried demand; (b) given a certain demand, and given a 100% restoration requirement, minimize the total capacity used. In our formulation, we minimize the total capacity used while providing 100% restoration guarantee for all possible double-link failures. Our objective is to minimize the total number of wavelengths used on all the links in the network (for both the primary and backup paths), measured by number of wavelength-links. 1 wavelength-link is a wavelength used on a link. The ILP solution determines the primary and backup paths for the demand set and hence the routing and wavelength assignment. ILP1, ILP2 minimize the capacity utilization for dedicated-link protection and shared-link protection schemes.

5.1 Notation

We define the notation employed to formulate the ILPs. We are given the following: (a) the network topology represented as a directed graph G, (b) a demand matrix, i.e. the number of lightpaths requests between node-pairs, and (c) alternate routing tables at each node. The following notations are used.

Notations:

$n = 1, 2, \ldots$ N : Number assigned to each node in the network

$j, k, l = 1, 2, \ldots$ L : Number assigned to each link in the network

$\lambda = 1, 2, \ldots$ W: Number assigned to each wavelength

$i = 1, 2, \ldots$ N(N –1): Number assigned to each s-d pair

K: Number of alternate routes ($K = 3$)

M: Number of alternate route between the node pair adjacent to link l ($M = 2$)

$p = 1, 2, \ldots$ KW: Number assigned to a path for each s-d pair. A path has an associated wavelength (lightpath). Each route between every s-d pair has W wavelength continuous paths. The first $1 \le p \le W$ paths belong to alternate route 1, $W \le p \le 2W$ paths belong to route 2 and $2W \le p \le 3W$ paths belong to route 3

$r = 1, 2, \ldots$ MW: Number assigned to an alternate path for each link. A path has an associated wavelength (lightpath). Each alternate route around link l has W wavelength continuous paths. The first $1 \leq p \leq W$ paths belong to alternate route 1, and $W \leq p \leq 2W$ paths belong to route 2

(*i, p*) refers to the *p*th path for s-d pair

(l, r), (j, r), (k, r) refers to the *r*th alternate route for link l, j, k respectively

d_i: Demand for node pair I, in terms of number of lightpath requests.

The following notations are used for path related information.

$\delta^{i,p}$: Path indicator, which takes a value one if (*i, p*) is chosen as a primary path and zero otherwise (binary variable)

$v^{l,r}$: Path indictor, which takes a value one if *(l, r)* is chosen as a restoration path and zero otherwise (binary variable).

$\varepsilon_l^{i,p}$: Link indicator, which takes a value one if link *l* is used by the path (*i, p*) and zero otherwise (data)

$\psi_\lambda^{i,p}$: Wavelength indicator, which takes a value one if λ is used by the path (*i, p*) and zero otherwise

$g_{l,\lambda}$: Takes a value one if wavelength λ used by some restoration path (*k, r*) that traverse link *l*, zero otherwise (binary variable)

$\varepsilon_l^{k,r}$: Link indictor which takes a value of one if link *l* is used in restoration path (*k, r*), one otherwise (binary data)

$\psi_\lambda^{k,r}$: Wavelength indicator, which takes a value one if wavelength λ is used by the restoration path (k, *r*) and zero otherwise (binary data)

s_l : Number of spare wavelengths used on link *l*

w_l : Number of wavelengths used by primary lightpaths on link l

5.2 Problem formulations

Objective: The objective is to minimize the total number of wavelengths used on all the links in the network (for both the primary and backup paths). The first term in objective function (Equation (1), Equation (9)) is the number of wavelengths used on primary paths that pass the link l, and the second term denotes the number of wavelengths used on backup paths that pass link l.

5.2.1 ILP1: Dedicated - link protection

Objective:

Minimize

$$\sum_{l=1}^{L}(w_l+s_l) \tag{1}$$

Link capacity Constraint:

$$w_l + s_l \le W \qquad 1 \le l \le L \tag{2}$$

Demand constraint for each node pair:

$$\sum_{p=1}^{KW} \delta^{i,p} = d_i \qquad 1 \le i \le N(N-1) \tag{3}$$

Primary link capacity constraint: Define the number of primary lightpaths traversing each link.

$$w_l = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \qquad 1 \le l \le L \tag{4}$$

Spare capacity constraint: Definition of spare capacity required on link l:

$$s_l = \sum_{r=1}^{MW} \sum_{k=1}^{L} v^{k,r} \varepsilon_l^{k,r} \qquad 1 \le l \le L \tag{5}$$

Primary path wavelength usage constraint: only one primary can use a wavelength λ on link l, no restoration path can use the same λ on link l.

$$\left(\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \delta_l^{i,p} \psi_\lambda^{i,p} \right) + \sum_{r=1}^{2W} \sum_{k=1}^{L} v^{k,r} \varepsilon_l^{k,r} \psi_\lambda^{k,r} \le 1 \qquad 1 \le l \le L \qquad 1 \le \lambda \le W \tag{6}$$

Demand constraints for each link l: There are two restoration routes for each link l, so that the demand on link l can be met after any double-link failures.

$$\sum_{r=1}^{W} v^{l,r} \psi_\lambda^{l,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \psi_\lambda^{i,p} \qquad 1 \le \lambda \le W \quad 1 \le l \le L \tag{7}$$

$$\sum_{r=W+1}^{2W} v^{l,r} \psi_\lambda^{l,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \psi_\lambda^{i,p} \qquad 1 \le \lambda \le W \quad 1 \le l \le L \tag{8}$$

5.2.2 ILP2: Shared -link protection

Objective :

Minimize

$$\sum_{l=1}^{L} (w_l + s_l) \tag{9}$$

Link capacity Constraint:

$$w_l + s_l \le W \qquad 1 \le l \le L \tag{10}$$

Demand Constraint for each node pair:

$$\sum_{p=1}^{KW} \delta^{i,p} = d_i \qquad 1 \le i \le N(N-1) \tag{11}$$

Primary link capacity constraint: Define the number of primary lightpaths traversing each link.

$$w_l = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \qquad 1 \le l \le L \qquad (12)$$

Spare capacity constraint: Definition of spare capacity required on link *l*.

$$s_l = \sum_{\lambda=1}^{W} g_{l,\lambda} \qquad 1 \le l \le L \qquad (13)$$

Primary path wavelength usage constraint: only one primary can use a wavelength λ on link *l*, no restoration path can use the same λ on link *l*.

$$\left(\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \psi_\lambda^{i,p} \right) + g_{l,\lambda} \le 1 \qquad 1 \le l \le L \qquad 1 \le \lambda \le W \qquad (14)$$

Restoration path wavelength usage constraint:

$$g_{l,\lambda} \le \sum_{k=1}^{L} \sum_{r=1}^{2W} v^{k,r} \varepsilon_l^{k,r} \psi_\lambda^{k,r} \qquad 1 \le l \le L \qquad 1 \le \lambda \le W \qquad (15)$$

$$LMW \ g_{l,\lambda} \ge \sum_{k=1}^{L} \sum_{r=1}^{2W} v^{k,r} \varepsilon_l^{k,r} \psi_\lambda^{k,r} \qquad 1 \le l \le L \qquad 1 \le \lambda \le W \qquad (16)$$

Demand constraint for link l: There are two restoration routes for each link *l*, so that the demand on link *l* can be met after any double–link failures.

$$\sum_{r=1}^{W} v^{l,r} \psi_\lambda^{l,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \psi_\lambda^{i,p} \qquad 1 \le \lambda \le W \qquad 1 \le j \le L \qquad (17)$$

$$\sum_{r=W+1}^{2W} v^{l,r} \psi_\lambda^{l,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \varepsilon_l^{i,p} \psi_\lambda^{i,p} \qquad 1 \le \lambda \le W \qquad 1 \le j \le \lambda \qquad (18)$$

Backup multiplexing constraint 1: if link *j* is not on the alternate routes of link *k* and *k* is not on the alternate routes of *j*, then the first backup route of link *j* and the first backup route of link *k* cannot wavelength channels on their common links (corresponding to backup multiplexing rule 1 in chapter 4:

$$\sum_{r=1}^{W} v^{j,r} \quad \psi_{\lambda}^{j,r} \quad \delta_{l}^{j,r} \; + \; \sum_{r=1}^{W} v^{k,r} \quad \psi^{k,r} \quad \delta_{l}^{k,r} \; \le \; 1$$

$1 \le j \le L,\ j+1 \le k \le L,\ 1 \le \lambda \le W,\ 1 \le l \le L,$ *j* is not on the alternates of *k*, *k* is not on the alternate routes of *j* (19)

Backup multiplexing constraint 2: if link *j* is not on the alternate routes of link *k* and *k* is on one of the alternate routes of *j*, then there should be no wavelength sharing between the backup route of *j*, which does not pass link *k*, and the first backup route of link *k* (corresponding to backup multiplexing rule 2 and rule 3 in chapter 4).

$$\sum_{r=1}^{2W} v^{j,r} \psi_{\lambda}^{j,r} (1- \;\; \varepsilon_{k}^{j,r}) \;\; \varepsilon_{l}^{j,r} \; + \; \sum_{r=1}^{W} v^{k,r} \quad \psi^{k,r} \quad \varepsilon_{l}^{k,r} \; \le \; 1$$

$1 \le j \le L,\ 1 \le k \le L,\ 1 \le \lambda \le W,\ 1 \le l \le L,$ j is not on alternates of k, k is on one of the alternate routes of j (20)

Backup multiplexing constraint 3: if link *j* is on one of the alternate routes of link *k* and *k* is on one of the alternate routes of *j*, then there should be no wavelength sharing between the backup route of *j*, which does not pass link *k*, and the backup route of link *k*, which does not pass link *j* (corresponding to backup multiplexing rule 4 in chapter 4).

$$\sum_{r=1}^{2W} v^{j,r} \psi_{\lambda}^{j,r} (1- \;\; \varepsilon_{k}^{j,r}) \;\; \varepsilon_{l}^{j,r} \; + \; \sum_{r=1}^{2W} v^{k,r} \quad \psi^{k,r} (1- \;\; \varepsilon_{j}^{k,r}) \;\; \varepsilon_{l}^{k-r} \; \le \; 1$$

$1 \le j \le L,\ j+1 \le k \le L,\ 1 \le \lambda \le W,\ 1 \le l \le L,$ *j* is on one of alternate routes of *k*, *k* is on one of the alternate routes of *j* (21)

6. RESULTS AND DISCUSSION

We use CPLEX Linear Optimizer 5.0.1 [22] to solve the ILPs. The combined routing and wavelength assignment problem is known to be NP-Complete [23] and the problems addressed in this paper are expected to be NP-Complete as well. The number of variables and the number of equations for the ILPs grow rapidly with the size of the network. Therefore, the ILP formulations are practical only for a small network (a few tens of nodes). For larger network, we need to employ decomposition methods or use heuristic methods [13] [24] [25] [26] [27]. We first demonstrate the working of the ILPs through an example and then show results on a 11-node 21-link network, which is modified form of the NJ LATA network, as shown in Figure 5.

6.1 An illustration

We present an illustration to understand the working of the ILP and to demonstrate the capacity savings obtained by shared link protection for double-link failures. Consider a simple 5-node network with one fiber per link and 3 wavelengths per fiber, shown in Figure 4.

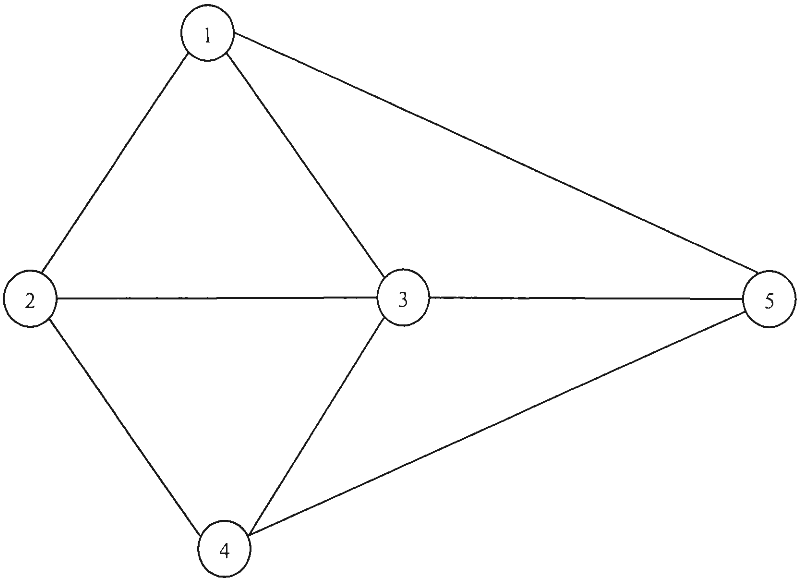


Figure 4. The 5-node 8-link network

To understand the ILP solution, assume that each of four node pairs 1, 5, 13, 20 have one lightpath request between them. There are 20 node pairs (5 nodes, each can have 4 destinations). They are numbered sequentially. We can determine the source and destination for node pair *r* use following relationships: For a node pair *r*, the source node number *i* = $\left\lceil \frac{r}{N-1} \right\rceil$, *N* is the total number of node pairs. Let $k = r-(i-1)*(N-1)$, then destination node number $j = k$, if $k < j$, else $j = k+1$.

The routes and wavelengths of primary and backup lightpaths for the dedicated-link protection (as solved by ILP1) are illustrated in Table 1. The routes and wavelengths of primary and backup lightpaths for the shared-link protection (as solved by ILP1) for the same demand are illustrated in Table 2. The first column is the number of connections for each node pair. The second column is the primary path and assigned wavelength on the path obtained from the ILP formulation. The third column indicates the links on the primary path for each node pair. The fourth column indicates the first backup path for each link in third column. The fifth column indicates the second backup path for each link in third column.

Table 1. The routes and wavelengths of primary and backup paths under dedicated-link protection

Node pair	Primary Lightpath	Links	Backup lightpath1	Backup lightpath2
1	(1, 2) --- λ3	(1, 2)	(1, 3, 2) --- λ3	(1, 5, 4, 2) --- λ3
5	(2, 1) --- λ3	(2, 1)	(2, 3, 1) --- λ3	(2, 4, 5, 1) --- λ3
13	(4, 3, 1) --- λ1	(4, 3)	(4, 2, 3) --- λ1	(4, 5, 3) --- λ1
		(3, 1)	(3, 2, 1) --- λ1	(3, 5, 1) --- λ1
20	(5,4) --- λ2	(5, 4)	(5, 3, 4) --- λ2	(5, 1, 2, 4) ---λ2

Table 2. The routes and wavelengths of primary and backup paths under shared-link protection

Node pair	Primary Lightpath	Link s	Backup lightpath1	Backup lightpath2
1	(1, 2) --- λ3	(1, 2)	(1, 3, 2) --- λ3	(1, 5, 4, 2) --- λ3
5	(2, 1) --- λ2	(2, 1)	(2, 3, 1) --- λ2	(2, 4, 5, 1) --- λ2
13	(4, 5, 1) --- λ3	(4, 5)	(4, 3, 5) --- λ3	(4, 2, 1, 5) --- λ3
		(5, 1)	(5, 3, 1) --- λ3	(5, 4, 2, 1) --- λ3
20	(5, 4) --- λ2	(5, 4)	(5, 3, 4) --- λ2	(5, 1, 2, 4) ---λ2

For each link on the primary paths, two backup paths are provided and wavelengths are reserved on these paths. In Table 1, each reserved wavelength on a link of backup paths is dedicated to a link on a primary path. For example, $\lambda3$ on link (2, 4) is reserved and dedicated to link (2,1), which is a link on primary path 2 -> 1. $\lambda2$ on link (2, 4) is reserved and dedicated to link (5, 4), which is a link on primary path 5 -> 4. In contrast, in Table 2, λ_2 on link (2, 4) is shared by backup path 2 -> 4 -> 5 -> 1 and backup path 5 -> 1 -> 2 -> 4. The path 2 -> 4 -> 5 -> 1 is the second backup path for link (2, 1) on primary path 2 -> 1, while the path 5 -> 1-> 2-> 4 is the second backup path for link (5, 4) on primary path 5 -> 4. Therefore one backup wavelength is saved by sharing the wavelength on the common link in shared-link protection scheme.

An interesting observation is that the primary path for node pair 13 in shared – link protection is different from the primary path for node 13 in dedicated – link protection. The reason is that routing primary for request 13 on path 4 -> 5 -> 1 rather than on 4 -> 3 -> 1 has more wavelength sharing on the backup paths, thus leads to minimum capacity utilization for this demand. The shared-link protection scheme utilizes a total of 23 wavelength - links (1 wavelength - link is a wavelength used on a link), while the dedicated - link protection scheme utilizes a total of 28 wavelength - links for this demand. The shared – link protection saves about 18% capacity.

6.2 Results on modified NJ LATA Network

We demonstrate results on the 11-node 21-link network, which is a modified form of NJ LATA network as shown in Figure 5.

6.2.1 An example ILP solution

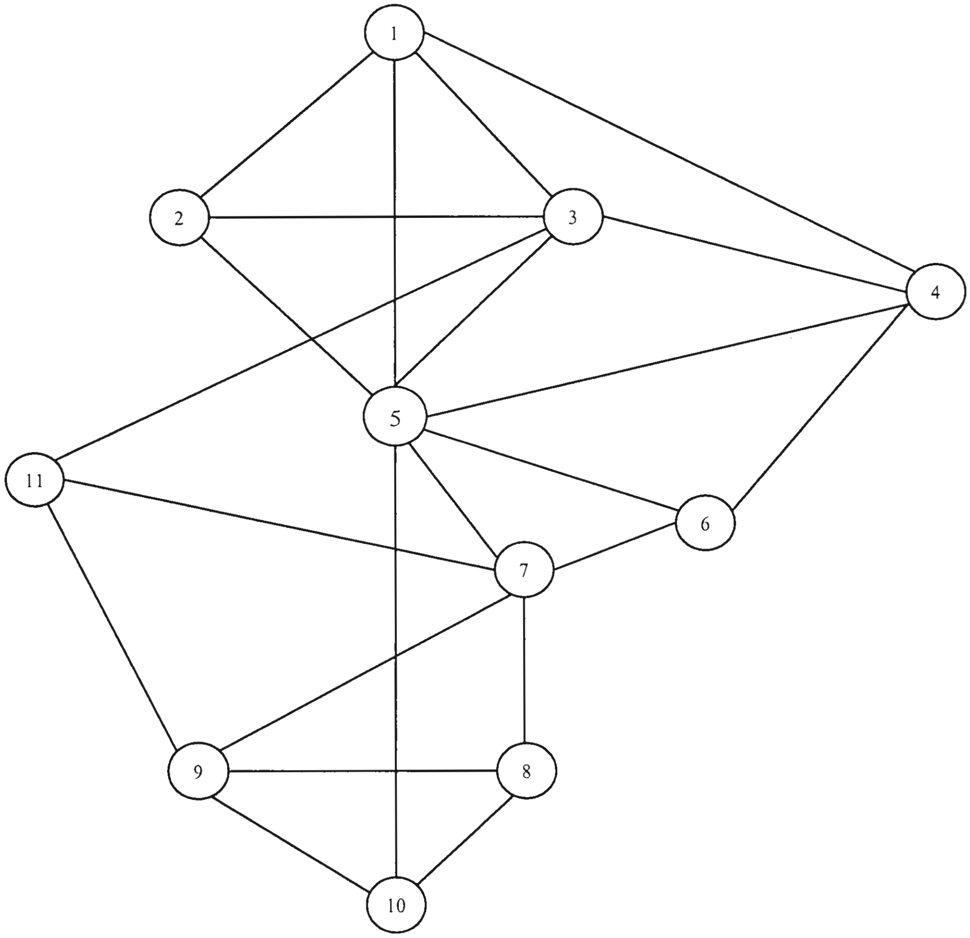


Figure 5 A network with 11 nodes and 21 links

First let us assume the network has one fiber per link and 10 wavelengths per fiber. We demonstrate the solution assuming a traffic demand on five node pairs, and each pair requests 5 connections. The node pairs are 1, 11, 33, 50, 89. The route and wavelength assignment of primary and backup lightpaths for the dedicated-link protection produced by ILP1 for the given traffic demand is shown in Table 3. The routes and wavelength assignment of primary and backup lightpaths for the shared-link protection as solved using ILP2 for the same demand set is shown in Table 4.

Table 3. The routes and wavelengths of primary and backup paths under dedicated-link protection

Node pair	Primary Lightpath	Links	Backup lightpath1	Backup lightpath2
1	(1, 2) --- λ1, λ2, λ4, λ5, λ6	(1, 2)	(1, 3, 2) --- λ1, λ2, λ4, λ5, λ6	(1, 5, 4, 2) --- λ1, λ2, λ4, λ5, λ6
11	(2, 1) --- λ1, λ2, λ4, λ5, λ6	(2, 1)	(2, 3, 1) --- λ1, λ2, λ4, λ5, λ6	(2, 4, 5, 1) --- λ1, λ2, λ4, λ5, λ6
33	(4, 3) --- λ3, λ7, λ8, λ9, λ10	(4, 3)	(4, 2, 3) --- λ3, λ7, λ8, λ9, λ10	(4, 5, 3) --- λ3,λ7, λ8, λ9, λ10
50	(5, 7, 11) --- λ1, λ2, λ4, λ5, λ6	(5, 7)	(5, 6, 7) --- λ1, λ2, λ4, λ5, λ6	(5, 10, 8, 7) --- λ1, λ2, λ4, λ5, λ6
		(7,11)	(5, 6, 7) --- λ1, λ2, λ4, λ5, λ6	(5, 10, 8, 7) --- λ1, λ2, λ4, λ5, λ6
89	(9, 10) --- λ3, λ7, λ8, λ9, λ10	(9,10)	(9, 8, 10) --- λ3, λ7, λ8, λ9, λ10	(9, 7, 5, 10) --- λ3,λ7, λ8, λ9, λ10

In Table 4, reserved wavelengths are shared by corresponding backup path pair on links (4,2), (4,5), (5,3), (7,5), (5,10). Shared-link protection scheme uses a total of 150 wavelength-links, while dedicated-link protection scheme uses a total of 175 wavelength-links. Shared-link protection provides about 15% improvement in capacity utilization for this demand set.

Table 4. The routes and wavelengths of primary and backup paths under shared-link protection

Node pair	Primary Lightpath	Links	Backup lightpath1	Backup lightpath2
1	(1, 2) --- λ2, λ3, λ6, λ7, λ8	(1, 2)	(1, 3, 2) --- λ2, λ3, λ6, λ7, λ8	(1, 5, 4, 2) --- λ2, λ3, λ6, λ7, λ8
11	(2, 1) --- λ2, λ3, λ6, λ7, λ8	(2, 1)	(2, 3, 1) --- λ2, λ3, λ6, λ7, λ8	(2, 4, 5, 1) --- λ2, λ3, λ6, λ7, λ8
33	(4, 3) --- λ2, λ3, λ6, λ7, λ8	(4, 3)	(4, 2, 3) --- λ2, λ3, λ6, λ7, λ8	(4, 5, 3) --- λ2, λ3, λ6, λ7, λ8
50	(5, 7, 11) --- λ2, λ3, λ6, λ7, λ8	(5, 7)	(5, 6, 7) --- λ2, λ3, λ6, λ7, λ8	(5, 10, 8, 7) --- λ2, λ3, λ6, λ7, λ8
		(7, 11)	(5, 6, 7) --- λ2, λ3, λ6, λ7, λ8	(5, 10, 8, 7) --- λ2, λ3, λ6, λ7, λ8
89	(9, 10) --- λ2, λ3, λ6, λ7, λ8	(9,10)	(9, 8, 10) --- λ2, λ3, λ6, λ7, λ8	(9, 7, 5, 10) --- λ2, λ3, λ6, λ7, λ8

6.2.2 Saving of backup capacity for shared-link protection scheme

We now assume that the network has one fiber per link and 25 wavelengths per fiber. We demonstrate our solution on a traffic demand matrix spread over 10 node pairs. The capacity improvements obtained are shown in Table 5. The first column indicates the number of connections in the demand. The second column indicates the capacity utilization of the optimal routing and wavelength assignment of the lightpaths obtained from the ILP formulation for dedicated-link protection scheme. The third column indicates the capacity utilization of the optimal routing and wavelength assignment of the lightpaths obtained from the ILP formulation for shared-link protection scheme. The fourth column is the improvement by the shared-link protection scheme over the dedicated scheme. We were able to obtain significant improvements in capacity utilization because we identified rules that enable backup wavelength sharing under different failure scenarios. These were effectively captured in the problem formulation that results in capacity savings.

Table 5. Comparison of capacity utilization for dedicated and shared-link protection schemes

No. of connections	Dedicated	Shared	Improvement
20	135	120	11.1%
30	198	178	10.1%
40	275	240	12.7%
50	334	299	10.5%
60	412	366	10.8%
70	480	420	12.6%

7. SUMMARY AND CONCLUSION

Network survivability is a crucial requirement in high-speed optical networks. Recently, there has been research in approaches for surviving double-link failures. In this thesis, we first reviewed a double-link failure model and three link based protection methods in literature. The basic idea behind these methods is to pre-compute two backup paths for each link on the primary paths and reserve resources on these paths. Compared to protection methods for single-link failure model, the protection methods for double-link failure model require much more spare capacity. Reserving dedicated resources on every backup path at the time of establishing primary path itself would reserve excessive resources. We used these double-link failure recovery methods, identified rules for backup multiplexing in the double-link failure recovery model. To optimize the capacity utilization, we formulated ILPs to determine the capacity utilization for dedicated and shared-link protection schemes under the assumption that 100% protection guarantee is needed. The numerical results obtained for a representative network topology and for randomly picked demand sets indicate that shared link protection scheme provides 10-15% savings on capacity utilization over dedicated-link protection scheme. We provide a way of adapting the heuristic based double-link failure recovery method into a mathematical framework, and use technique to improve wavelength utilization for optimal capacity usage.

Future Work

1. To demonstrate the effectiveness of capacity saving by the backup multiplexing in a real network. The 20-node and 32-link ARPANET network is not 3-connected network, but has no ordered cut-set. It is potentially recoverable for double-link failures. Some of node pairs do not have three alternate routes, but every link has two alternate routes around itself. Thus the restoration method used in this thesis is applicable to this kind of network. However, the variables and equations grow larger with 32 links and 20 nodes. We need to adopt heuristic and decomposition techniques.

2. Path based restoration methods to tolerate double-link failures could be another interesting direction. The study of advantages and disadvantages between the link-based and path-based double-link failures restoration methods could yield some insight for improving the survivability of optical networks.

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