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

Wensheng He, Murari Sridharan, and Arun K. Somani

Dependable Computing & Networking Laboratory
Department of Electrical & Computer Engineering
Iowa State University, Ames, Iowa 50011

ABSTRACT

Most research to date in survivable optical network design and operation, 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.[1] 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 consume excessive resources.

In Ref. 2 and 3, we captured the various operational phases in survivable WDM networks as a single integer programming based (ILP) optimization problem. In this work, we extend our optimization framework to include double-link failures. We use the double-link failure recovery methods available in literature, employ backup multiplexing schemes to optimize capacity utilization, and provide 100% protection guarantee for double-link failure recovery. We develop rules to identify scenarios when capacity sharing among interacting demand sets is possible. Our results indicate that for the double-link failure recovery methods, the shared-link protection scheme provides 10-15% savings in capacity utilization over the dedicated link protection scheme which reserves dedicated capacity on two backup paths for each link. We provide a way of adapting the heuristic based double-link failure recovery methods into a mathematical framework, and use techniques to improve wavelength utilization for optimal capacity usage.

Keywords: WDM, protection, restoration, survivability, double-Link failures, optimization, ILP

1. INTRODUCTION

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.[4] The challenge is to react quickly to these increasing bandwidth requirements while maintaining reliable service. 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 upto 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.[5] There are 40-channel DWDM systems commercially available,[6] 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. If wavelength translation is performed in optical switching, then each channel may be

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Further author information: (Send correspondence to Arun K. Somani)
Arun K. Somani: E-mail: arun@iastate.edu

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 paper, we assume that there is no wavelength translation in the network.

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 which 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.

1.1. 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.[1] 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 Ref. 2 and 3, we captured the various operational phases in survivable WDM networks as a single ILP problem. This framework also captured service disruption aspects. In this work, we extend our integer programming framework to include double-link failures. We use backup multiplexing schemes to optimize capacity utilization and provide 100% protection guarantee for double-link failure recovery.

1.2. Outline of the paper

The remainder of Section 1 reviews prior work on survivable optical networks. Section 2 details the double-link restoration model adopted for our formulation. In Section 3, we develop the ILP formulation for capacity optimization by improving wavelength utilization for the double-link restoration model. Section 4 provides results to demonstrate the improvements obtained in capacity utilization by optimal wavelength sharing over the dedicated protection case. Section 5 presents our conclusions.

1.3. Related Work

Several survivability paradigms have been explored for surviving single link failures in mesh-based networks.[7–11] They can be classified based on their route computation and execution mechanisms as centralized/distributed, by their re-routing as path/link based, by their computation timing as pre-computed/real time, and their capacity sharing as dedicated/shared. Link based restoration methods re-route disrupted traffic around the failed link, while path based re-routing replaces the whole path between the source and destination of a demand. Link based approach requires the ability to identify a failed link at both ends and makes restoration more difficult when node failures happen. The choice of restoration paths is limited, and thus may use more capacity. The pre-computed approach calculates restoration paths before a failure happens and real time approach does so after the failure occurs. The former approach allows fast restoration as the routes are pre-computed, while the latter approach is slow, as the alternate route is computed after the failure is detected. Centralized restoration methods compute primary and restoration paths for all demands at a central controller where current information is assumed to be available. The routes are then downloaded into each node's route tables. They may use pre-computed routes or detect routes at real time. Centralized schemes which involve pre-computed routes are more conducive for practical implementations. However, maintaining up-to-date information requires frequent communications between the nodes and the central controller. This overhead becomes a potential problems as the network size grows. Distributed methods may involve pre-computed tables of routes, and discovers capacity in real time. Real time capacity discovery is usually slow and the capacity utilization may be inefficient. Distributed pre-computation of restoration route is an attractive approach. Capacity sharing among the primary and restoration paths can be dedicated or shared. The dedicated technique uses 1:1 protection where each primary path has a corresponding restoration path. In the shared case several primaries can share the same backup path as long

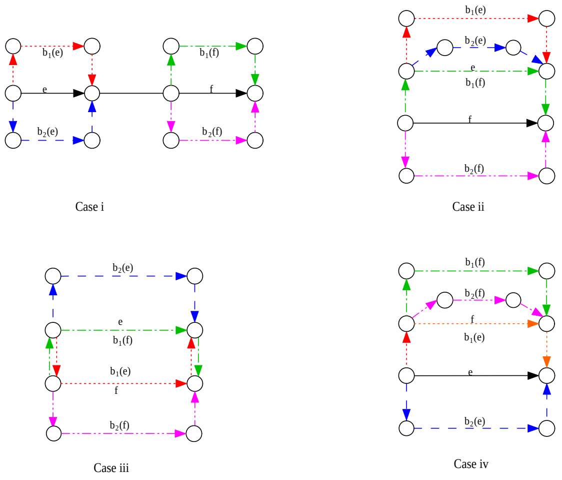

Figure 1. Four cases demonstrating rerouting of traffic on links e and f when they both fail

as the primaries are node and link disjoint. This scheme is sometimes called backup multiplexing technique. Recent approaches for protecting link failures can be found in Ref. 12-15.

Besides the recent work in Ref. 1, there has been some research in surviving two-link failures.[16–18] 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 Ref. 16. A hierarchical classification scheme for two-link failures in all optical networks was presented in Ref. 17. 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 Ref 18, 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.

2. BACKUP MULTIPLEXING IN DOUBLE-LINK FAILURE RECOVERY MODEL

Most research to date in survivable optical network design and operation, focused on the failure of a single component such as a link or a node. It is possible to have two links fail simultaneously. 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.[1]

Three link-based double-link failure recovery methods were presented in Ref. 1. For a graph to remain connected after any two edges fail, the graph must be 3-connected. By Menger's theorem,[19] 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 recovery from the first failure is completed. These methods also work when two links fail simultaneously. We review the three methods in the following section.

2.1. Backup Paths with Link Identification - Methods I and 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 (Figure 1).

1. $b_1(f)$ 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.

2. $b_1(f)$ 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.

3. $b_1(f)$ 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 traffic 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 $(b_1(e) - f) \cup b_2(f)$.

4. $b_1(f)$ does not use e, f lies on $b_1(e)$: Similar to case 3, 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, $(b_1(e) - f) \cup b_1(f)$ 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.

2.2. 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 $b(f)$ which 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 be traverse many links.

Computing such kind of backup paths is not trivial. A heuristic algorithm was developed in Ref.1 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.

2.3. Backup Multiplexing in Double-Link Failure 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 wavelengths on their common links without violating of 100% protection guarantee. For each of the cases illustrated in Section 2.1, we need to identify scenarios where backup multiplexing is possible without violating protection guarantees.

Let us consider case (1) in Section 2.1. For convenience we state the case (1) again. For any two links e and f, $b_1(f)$ does not use e, f does not lie on $b_1(e)$. Without loss of generality, let us assume that link e fails first. The following scenarios can occur.

1. Link 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. Link e fails first, then one of links $g \in b_1(e)$ 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. Link 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.

As can be seen from the above scenarios, only paths $b_1(e)$ and $b_1(f)$ are used simultaneously (as in failure scenario 1). All 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. Thus, if one of above path pairs, which are not used simultaneously, have any common link(s), then they can share the reserved backup wavelengths on the common link(s). Similar rules of sharing backup wavelengths on common links can be obtained for the cases (2), (3), and (4) in Section 2.1 as well. These rules for backup multiplexing are captured in the ILP formulation as shown in Section 3 (Equations (19), (20), and (21)).

3. PROBLEM FORMULATION

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

The following information is assumed to be given: the network topology, 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 pre-computed and given. Each route between every node pair is viewed as W wavelength continuous paths (lightpaths), one for each wavelength, and therefore, we do not have an explicit constraint for wavelength continuity. In our formulation, we minimize the total capacity used while providing 100% protection 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. one wavelength link represents 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 and ILP2 minimize the capacity utilization for dedicated link protection and shared link protection schemes, respectively.

3.1. Notation

The network topology is represented as a directed graph $G(N, L)$ with N nodes and L links with W wavelengths on each link. The following notations are used.

- $n = 1, 2 \ldots, N$: 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
- $K = 3$: Number of alternate routes between every s-d pair
- $M = 2$: Number of alternate routes for the link l
- $p = 1, 2, \ldots, KW$: 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 $1 \leq p \leq W$ paths belong to route 1, $W + 1 \leq p \leq 2W$ paths belong to route 2 and $2W + 1 \leq p \leq 3W$ paths belong to route 3
- $r = 1, 2, \ldots, MW$: Number assigned to a 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 $1 \leq r \leq W$ paths belong to alternate route 1, $W + 1 \leq r \leq 2W$ paths belong to alternate route 2
- (i, p) : Refers to the pth path for s-d pair i

- (l,r),(j,r),(k,r) : Refers to the rth alternate path for the links 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, zero otherwise (binary variable)
- $\nu^{l,r}$: Path indicator which takes a value one if (l,r) is chosen as a restoration path, zero otherwise (binary variable)
- $\epsilon_l^{i,p}$: Link indicator, which takes a value one if link l is used in path (i,p), zero otherwise (data)
- $\psi_\lambda^{i,p}$: Wavelength indicator, which takes a value one if wavelength λ is used by the path (i,p), zero otherwise (data)
- $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration routes that traverses link l (binary variable)
- $\epsilon_l^{k,r}$: Link indicator, which takes a value one if link l is used in restoration path (k,r), zero otherwise (data)
- $\psi_\lambda^{l,r}$: Wavelength indicator, which takes a value one if wavelength λ is used by the restoration path (l,r), zero otherwise (data)
- s_l: Number of wavelengths used by backup lightpaths, which pass link l (variable)
- w_l: Number of wavelengths used by primary lightpaths, which pass link l (variable)

3.2. 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

3.2.1. ILP1: Dedicated Link Protection

Minimize

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

Link capacity constraint:

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

Demand constraint for each node pair:

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

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

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

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

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

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

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + \sum_{r=1}^{2W} \sum_{k=1}^{L} \nu^{k,r} \epsilon_l^{k,r} \psi_\lambda^{k,r} \le 1 \tag{6}$$
$$1 \le l \le L, 1 \le \lambda \le W$$

Demand constraints 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.

$$\sum_{r=1}^{W} \nu^{l,r} \psi_\lambda^{k,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} \tag{7}$$
$$1 \le l \le L, 1 \le \lambda \le W$$

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

3.2.2. ILP2: Shared Link Protection

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.

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

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

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

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

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

Restoration path wavelength usage constraint:

$$g_{l,\lambda} \leq \sum_{r=1}^{2W} \sum_{k=1}^{L} \nu^{k,r} \epsilon_l^{k,r} \psi_\lambda^{k,r} \qquad (15)$$
$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

$$N(N-1)KW g_{l,\lambda} \geq \sum_{r=1}^{2W} \sum_{k=1}^{L} \nu^{k,r} \epsilon_l^{k,r} \psi_\lambda^{k,r} \qquad (16)$$
$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

Demand constraints 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.

$$\sum_{r=1}^{W} \nu^{l,r} \psi_\lambda^{k,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} \qquad (17)$$
$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

$$\sum_{r=W+1}^{2W} \nu^{l,r} \psi_\lambda^{k,r} = \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} \qquad (18)$$
$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

Backup multiplexing constraint 1: if link j is not on the alternate routes of link k and k is not on alternate routes of j, then the first backup route of link j and the first backup route of link k cannot share wavelength channel on their common links (represents backup multiplexing rule for case (1) in Section 2.1).

$$\sum_{r=1}^{W} \nu^{j,r} \psi_\lambda^{j,r} \epsilon_l^{j,r} + \sum_{r=1}^{W} \nu^{k,r} \psi_\lambda^{k,r} \epsilon_l^{k,r} \leq 1 \qquad (19)$$
$$1 \leq j \leq L, j+1 \leq k \leq L, 1 \leq l \leq L, 1 \leq \lambda \leq W$$

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 (represents backup multiplexing rule for case (2) and (4) in Section 2.1).

$$\sum_{r=1}^{2W} \nu^{j,r} \psi_\lambda^{j,r} \epsilon_l^{j,r} (1 - \epsilon_k^{j,r}) + \sum_{r=1}^{W} \nu^{k,r} \psi_\lambda^{k,r} \epsilon_l^{k,r} \leq 1 \qquad (20)$$
$$1 \leq j \leq L, 1 \leq k \leq L, 1 \leq l \leq L, 1 \leq \lambda \leq W$$

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 link j, which does not pass link k, and the backup route of link k, which does not pass the link j (represents backup multiplexing rule for case (3) in Section 2.1).

$$\sum_{r=1}^{2W} \nu^{j,r} \psi_\lambda^{j,r} \epsilon_l^{j,r} (1 - \epsilon_k^{j,r}) + \sum_{r=1}^{2W} \nu^{k,r} \psi_\lambda^{k,r} \epsilon_l^{k,r} (1 - \epsilon_j^{k,r}) \leq 1 \qquad (21)$$
$$1 \leq j \leq L, j+1 \leq k \leq L, 1 \leq l \leq L, 1 \leq \lambda \leq W$$

4. RESULTS

We use CPLEX Linear Optimizer 5.0.1[20] to solve the ILPs. The combined routing and wavelength assignment problem is known to be NP-Complete.[21] 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.[8, 22–25] 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 3.

4.1. 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, as shown in Figure 2.

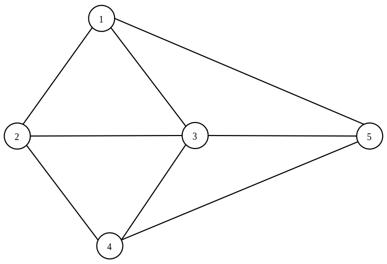

Figure 2. A 5-node 8-link network

To understand the ILP solution, assume that four node pairs, each having one lightpath request between them. 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 ILP2) for the same demand set are illustrated in Table 2.

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

Node pair	Primary lightpath	Links	Backup lightpath 1	Backup lightpath 2
1	(1,2)—λ_3	(1,2)	(1,3,2)—λ_3	(1,5,4,2)—λ_3
5	(2,1)—λ_3	(2,1)	(2,3,1)—λ_3	(2,4,5,1)—λ_3
13	(4,3,1)— λ_1	(4,3)	(4,2,3)—λ_1	(4,5,3)—λ_1
		(3,1)	(3,2,1)—λ_1	(3,5,1)—λ_1
20	(5,4)—λ_2	(5,4)	(5,3,4)—λ_2	(5,1,2,4)—λ_2

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

Node pair	Primary lightpath	Links	Backup lightpath 1	Backup lightpath 2
1	(1,2)—λ_3	(1,2)	(1,3,2)—λ_3	(1,5,4,2)—λ_3
5	(2,1)—λ_2	(2,1)	(2,3,1)—λ_2	(2,4,5,1)—λ_2
13	(4,5,1)— λ_3	(4,5)	(4,3,5)—λ_3	(4,2,1,5)—λ_3
		(5,1)	(5,3,1)—λ_3	(5,4,2,1)—λ_3
20	(5,4)—λ_2	(5,4)	(5,3,4)—λ_2	(5,1,2,4)—λ_2

For each link on the primary path, 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, λ_3 on link $(2,4)$ is reserved and dedicated to link $(2,1)$, which is a link on primary path $2 \rightarrow 1$. Similarly, λ_2 on link $(2,4)$ is reserved and dedicated to link $(5,4)$, which is a link on primary path $5 \rightarrow 4$. In contrast, in Table 2, λ_2 on link $(2,4)$ is shared by backup path $2 \rightarrow 4 \rightarrow 5 \rightarrow 1$ and backup path $5 \rightarrow 1 \rightarrow 2 \rightarrow 4$. The path $2 \rightarrow 4 \rightarrow 5 \rightarrow 1$ is the second backup path for link $(2,1)$ on primary path $2 \rightarrow 1$, while the path $5 \rightarrow 1 \rightarrow 2 \rightarrow 4$ is the second backup path for link $(5,4)$ on primary path $5 \rightarrow 4$. 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 pair 13 in dedicated link protection. The reason is that routing primary for request 13 on path $4 \rightarrow 5 \rightarrow 1$ rather than on $4 \rightarrow 3 \rightarrow 1$ has better wavelength sharing on the backup paths. This leads to minimum capacity utilization for this demand. The shared link protection scheme utilizes a total of 23 wavelength links, while the dedicated link protection scheme utilizes a total of 28 wavelength links for this demand. The shared link protection saves about 18% capacity.

4.2. 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 3.

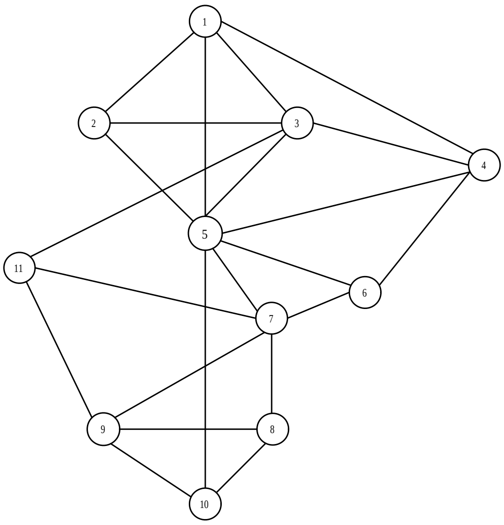

Figure 3. A 11-node 21-link modified NJ LATA network

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, which have five lightpath requests each. 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 paths for the shared link protection as solved using ILP2 for the same demand set is shown in Table 4. 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. This provides a 15% improvement in capacity utilization for the given demand set.

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

Table 3. The routes and wavelengths of primary and backup paths under dedicated-link protection for the modified NJ LATA network

Node pair	Primary lightpath	Links	Backup lightpath 1	Backup lightpath 2
1	(1,2)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(1,2)	(1,3,2)— $\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(1,5,4,2)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$
11	(2,1)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(2,1)	(2,3,1)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(2,4,5,1)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$
33	(4,3)$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$	(4,3)	(4,2,3)$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$	(4,5,3)—$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$
50	(5,7,11)— $\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(5,7)	(5,6,7)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(5,10,8,7)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$
		(7,11)	(7,9,11)—$\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$	(7,5,3,11)— $\lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6$
89	(9,10)$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$	(9,10)	(9,8,10)$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$	(9,7,5,10)—$\lambda_3, \lambda_7, \lambda_8, \lambda_9, \lambda_{10}$

Table 4. The routes and wavelengths of primary and backup paths under shared-link protection for the modified NJ LATA network

Node pair	Primary lightpath	Links	Backup lightpath 1	Backup lightpath 2
1	(1,2)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(1,2)	(1,3,2)— $\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(1,5,4,2)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$
11	(2,1)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(2,1)	(2,3,1)— $\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(2,4,5,1)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$
33	(4,3)$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(4,3)	(4,2,3)$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(4,5,3)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$
50	(5,7,11)— $\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(5,7)	(5,6,7)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(5,10,8,7)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$
		(7,11)	(7,9,11)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(7,5,3,11)— $\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$
89	(9,10)$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(9,10)	(9,8,10)$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$	(9,7,5,10)—$\lambda_2, \lambda_3, \lambda_6, \lambda_7, \lambda_8$

in Table 5. 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 which results in capacity savings.

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

No. of connections	Dedicated-link	Shared-link	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%

5. CONCLUSION

We reviewed double-link failures model and three link based protection methods in literature. We used these double-link failure recovery methods available in literature, 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. 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 are currently working on heuristics and decomposition techniques for solving larger problem instances using our optimization framework.

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