

Path-Based Protection for Surviving Double-Link Failures in Mesh-Restorable Optical Networks

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Abstract— we consider path-based protection methods for two-link failures in mesh optical networks. Two link-disjoint backup paths are pre-computed for each source and destination node pair. We identify the scenarios where the backup paths can share their wavelengths without violating 100% restoration guarantee (backup multiplexing). We use integer programming to optimize the total capacity requirement for both dedicated- and shared-path protection schemes. Our results indicate that backup multiplexing significantly improves the efficiency of total capacity utilization. For the randomly generated demand sets, the shared-path scheme provides up to 37.5% saving in total capacity utilization over dedicated-path scheme. Backup multiplexing provides more saving for the demand set that has connection requests distributed more evenly. For the double link failure recovery methods, path-based methods are more efficient in capacity utilization than link-based methods. Dedicated-path scheme performs better than shared-link scheme in total capacity utilization on average.

I. INTRODUCTION

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. A WDM optical network consists of a set of wavelength cross-connects interconnected by point-to-point fiber links. 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. Unlike a WSXC, a wavelength-interchange cross-connect (WISC) is capable of changing the wavelength of an incoming signal by using wavelength converters. In the absence of converters, the same wavelength has to be assigned on all links along the route. In this work, we assume that there is no wavelength translation in the network.

WDM networks are prone to component failures, and the failures would cause catastrophic effects due to the high volume of traffic. The protection methods for surviving link failures in mesh-based networks can be classified by their route computation and execution mechanisms as centralized or distributed, by their re-routing as path- or link-based, by their computation timing as pre-computed or real time, and by their capacity sharing as dedicated or shared [1][2][3]. There has been some research in surviving two-link failures. The problem of spare-channel design schemes for a self-healing network in the case of double link failures was solved using linear programming method in [4]. In [5], the two-link failures restorability of mesh networks designed to fully restore any single link failure was studied by experimental computational

approach. Three link-based protection methods were presented in [6]. In [7], three different models were developed to address the design of the networks for surviving dual failures. In our previous study[8], backup multiplexing technique was developed for link-based protection methods in the case of double-link failures. The total capacity for providing 100% protection was optimized. In this work, we present a path-based double-link failure recovery model. We first show that sharing backup resources among backup paths is possible, and then develop the rules to identify the scenarios when the sharing of backup capacity will not violate 100% restoration guarantee. We formulate the optimization of the total capacity utilization as an Integer Linear Programming (ILP) problem. Our results demonstrate the significant saving in total capacity by employing backup multiplexing technique.

II. DOUBLE-LINK FAILURE RECOVERY MODEL AND BACKUP MULTIPLEXING

A. Double-Link Failure Recovery Model

We consider a centralized recovery model with 100% restoration guarantee against any arbitrary two-link failures. The network is represented by a directed graph. For the graph to remain connected when two edges fail, the graph must be 3-connected. We assume this is the case. To provide 100% protection against any two-link failures, two link-disjoint backup paths must be provided for each $s-d$ pair. We assume that both links fail simultaneously (the model also works for the scenario when the second link fails during the physical repair of first failed link). We assume that each path, primary or backup, always accommodates an OAM (operation, administration, and maintenance) channel terminated at the same $s-d$ pair as the path. When a primary path fails, an alarm indication signal is generated by the node that detects the link failure and is transferred over OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to set up the first backup path. The first backup path may also fail due to another link failure. Therefore, run time search is needed. Run time search also detects if the backup capacity on the first backup path is not available due to the sharing, in the case of shared-path scheme (detailed in the following). If the source detects the above scenarios using run time search, it will prepare to set up the second backup path; otherwise, it will use the first backup path to reroute the traffic on the primary. The backup paths may or may not use the same wavelength as the primary path.

B. Backup Multiplexing

Reserving dedicated capacity on two backup paths for every primary path, however, could reserve excessive capacity in some situations. Fig.1 depicts an example to illustrate this problem. Suppose paths $1 \rightarrow 3 \rightarrow 2$ and $4 \rightarrow 5 \rightarrow 1$ are

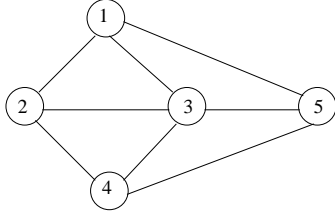


Fig. 1. A 5-node 8-link network

two primary paths p and r . $1 \rightarrow 2$ and $1 \rightarrow 5 \rightarrow 4 \rightarrow 2$ are two backup paths for p , denoted as b_{p1} , b_{p2} . $4 \rightarrow 3 \rightarrow 1$ and $4 \rightarrow 2 \rightarrow 1$ are two backup paths for r , denoted as b_{r1} , b_{r2} . The only failure scenario that could cause two primary paths to go down simultaneously is when one of links on p , and one of the links on r fail at the same time. b_{p1} and b_{r1} can be used to reroute the working traffic on p and r , respectively. Thus b_{p2} and b_{r2} will not be used at the same time for all possible two-link failures, therefore they can share backup capacity for primary p and r on link (4,2). On the other hand, backup capacity sharing is not always allowed if we want to provide 100% restoration guarantee against any two-link fails. Suppose the other two primary paths p and r are $2 \rightarrow 3 \rightarrow 1$ and $4 \rightarrow 5 \rightarrow 1$, respectively. The two backup paths for p are, b_{p1} : $2 \rightarrow 1$, and b_{p2} : $2 \rightarrow 4 \rightarrow 5 \rightarrow 1$. The two backup paths for r are, b_{r1} : $4 \rightarrow 2 \rightarrow 1$, b_{r2} : $4 \rightarrow 3 \rightarrow 1$. Since p and b_{r2} have shared links, and so do r and b_{p2} , the failure of one link on p could cause b_{r2} to fail, and the failure of one link on r could cause b_{p2} to fail. If the above scenario occurs, b_{p1} and b_{r1} will be used to reroute the primary traffic on p and r , respectively. Therefore they must not share backup capacity even if they have common link (2,1).

Now we summarize the backup multiplexing rules.

1) *Primary p and r are link-disjoint:* Table I case 1-6 summarize the topology relationships and backup capacity sharing constraint. The following notations and equations are used to express the topology relations and backup capacity sharing constraint.

- 1) $p \cap r = \phi$: primary path p and r are link-disjoint; otherwise, they have shared link(s).
- 2) $BC(b_{pi})$: backup capacity reserved on backup path b_{pi} .
- 3) $BC(b_{pi}) \wedge BC(b_{rl}) = \phi$: backup paths b_{pi} and b_{rl} must not share backup capacity on their common link(s).

2) *Primary p and r are not link-disjoint:* In addition to the above constraint, the failure of the shared link of p and r will cause both p and r to go down simultaneously. The worst-case scenario is that one of the backup paths of p and one of the backup paths of r also have a common link and that link also fails, causing these two backup paths to fail at the same time. If the above failure scenario occurs, the other backup paths of p and r will be used to reroute the primary traffic on p and r ,

respectively. Therefore they must not share backup capacity. This scenario is summarized in case 7 of Table I.

TABLE I
THE TOPOLOGY RELATIONSHIPS, FAILURE SCENARIOS AND BACKUP CAPACITY SHARING CONSTRAINT

Primary paths topology relationships	Backup-primary, backup-backup topology relationships	Backup capacity sharing constraints
$p \cap r = \phi$	1. $b_{pi} \cap r \neq \phi$, $b_{rl} \cap p \neq \phi$, i and $l \in \{1, 2\}$	$BC(b_{pi}) \wedge BC(b_{rl}) = \phi$
	2. $b_{pi} \cap r \neq \phi$, $b_{rl} \cap p = \phi$, $b_{rm} \cap p \neq \phi$, i, l , and $m \in \{1, 2\}$, $l \neq m$	$BC(b_{pi}) \wedge BC(b_{rl}) = \phi$
	3. $b_{pi} \cap r = \phi$, $b_{pj} \cap r \neq \phi$, $b_{rl} \cap p = \phi$, $b_{rm} \cap p \neq \phi$, i, j, l , and $m \in \{1, 2\}$, $i \neq j$, $l \neq m$	$BC(b_{pi}) \wedge BC(b_{rl}) = \phi$
	4. $b_{pi} \cap r = \phi$, $b_{rl} \cap p = \phi$, $b_{rm} \cap p \neq \phi$, i, l , and $m \in \{1, 2\}$, $l \neq m$	$BC(b_{pj}) \wedge BC(b_{rl}) = \phi$, $j = 1$ or 2
	5. $b_{pi} \cap r = \phi$, $b_{rl} \cap p \neq \phi$, i and $l \in \{1, 2\}$	$BC(b_{pj}) \wedge BC(b_{rl}) = \phi$, $j = 1$ or 2
	6. $b_{pi} \cap r = \phi$, $b_{rl} \cap p = \phi$, i and $l \in \{1, 2\}$	$BC(b_{pj}) \wedge BC(b_{rm}) = \phi$, $j = 1$ or 2 , $m = 1$ or 2
$p \cap r \neq \phi$	In addition to the above primary- and backup cases, there is one backup-backup relationship we need to consider 7. $b_{pi} \cap b_{rl} = \phi$, $i, l \in \{1, 2\}$	$BC(b_{pj}) \wedge BC(b_{rm}) = \phi$, j and $m \in \{1, 2\}$, $j \neq i$, $m \neq l$

III. PROBLEM FORMULATION

In this section, we develop the ILP formulation to optimize the capacity utilization for both shared- and dedicated-path protection schemes.

A. Route Choices for Primary and Backup Paths

For the ILP to optimize the capacity utilization, a set of alternate routes for each node pair need to be provided as given information to the ILP. "Eligible routes" can be determined by using hop-limit and distance-limit[7]. The number of equations for the ILP grows rapidly as the number of eligible routes increases, especially in the case of existence of wavelength continuity constraint. In this work, three successive shortest link-disjoint routes for each node pair are pre-computed and this information is given to ILP. We are working to find the heuristics to reduce the complexity of ILPs caused by using more alternate routes and hope to present them in the future.

B. Problem Formulations

We assume the following information is given: (a) the network topology represented as a directed graph G , (b) a demand matrix, and (c) alternate routing tables at each node. Each of the three alternate routes between a s - d pair is viewed as W (number of wavelengths available on the link) wavelength continuous paths, and therefore, we do not have an explicit constraint for wavelength continuity. 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. We first define the notations used in ILPs.

- $l = 1, 2, \dots, L$: Number assigned to each link

- $\lambda = 1, 2, \dots, W$: Number assigned to each wavelength
- $i, j = 1, 2, \dots, N(N-1)$: Number assigned to s - d pair
- $K = 3$: Number of alternate routes between s - d pair
- $p, r = 1, 2, \dots, KW$: Number assigned to a path
- (i, p) : Refers to the p th path for s - d pair i
- d_i : Demand for node pair i
- $\delta^{i,p}$: It takes a value one if (i, p) is chosen as a primary path, zero otherwise (binary variable)
- $\nu^{j,r}$: It takes a value one if (j, 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 λ is used by the path (i, p) , zero otherwise (data)
- $g_{l,\lambda}$: It takes a value one if wavelength λ is used by some restoration routes that traverses link l (binary variable)
- s_l : Number of wavelengths used by backup lightpaths, which pass through link l (variable)
- w_l : Number of wavelengths used by primary lightpaths, which pass through link l (variable)
- $I_{(i,p)(j,r)}$: It takes a value one if paths (i, p) and (j, r) share link(s), zero otherwise. If $i = j$, then $p \neq q$ (data)
- $\alpha_{(i,p)(j,r)}$: The number of shared links between paths (i, p) and (j, r) (data)

1) *ILP1: Dedicated-Path Protection: Objective: Minimize*

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

Subject to

$$w_l + s_l \leq W \quad 1 \leq l \leq L \quad (2)$$

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

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

$$s_l = \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} \quad 1 \leq l \leq L \quad (5)$$

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + \sum_{j=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{j,r} \epsilon_l^{j,r} \psi_\lambda^{j,r} \leq 1 \quad 1 \leq l \leq L, 1 \leq \lambda \leq W \quad (6)$$

Demand constraint for node pair i There are two restoration routes for each primary call. Let $x, y, z \in \{0, 1, 2\}$ and $x \neq y \neq z$; $t, u, v \in \{x, y, z\}$, $t \neq u \neq v$:

$$\sum_{p=tW+1}^{(t+1)W} \delta^{i,p} + \sum_{p=uW+1}^{(u+1)W} \delta^{i,p} = \sum_{r=vW+1}^{(v+1)W} \nu^{i,r} \quad 1 \leq i \leq (N-1) \quad (7)$$

2) *ILP2: Shared-Path Protection*: It has the same objective and constraints (2),(3),(4) and (7) in *ILP1*. Equations (8)-(11) are needed to replace equations (5) and (6) to ensure that sharing of backup capacity is allowed.

$$s_l = \sum_{\lambda=1}^W g_{l,\lambda} \quad 1 \leq l \leq L \quad (8)$$

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + g_{l,\lambda} \leq 1 \quad (9)$$

$$g_{l,\lambda} \leq \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} \psi_\lambda^{i,r} \quad (10)$$

$$(N-1)KW g_{l,\lambda} \geq \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} \psi_\lambda^{i,r} \quad 1 \leq l \leq L, 1 \leq \lambda \leq W \quad (11)$$

For the following equations, let $m, n \in \{0, 1, 2\}$; $s, s' \in \{(m+1) \bmod 3, (m+2) \bmod 3\}$, $s \neq s'$; $t, t' \in \{(n+1) \bmod 3, (n+2) \bmod 3\}$, $t \neq t'$.

$$X_\lambda^{i,m} = \nu_\lambda^{i,mW+\lambda} \psi_\lambda^{i,mW+\lambda} \quad (12)$$

Constraint for backup multiplexing rules 1, 2 and 3 in Section II-B: if $I_{(i,s)(j,n)} = 1$, $I_{(i,m)(j,t)} = 1$ and $I_{(i,s')(j,t')} = 1$, then

$$X_\lambda^{i,s'} + X_\lambda^{j,t'} \leq 1 \quad 1 \leq i < j \leq N(N-1), 1 \leq \lambda \leq W \quad (13)$$

Constraint for backup multiplexing rules 4 and 5 in Section II-B: if $I_{(i,s)(j,n)} = 0$, $I_{(i,s')(j,n)} = 0$, $I_{(i,m)(j,t)} = 1$, $I_{(i,s)(j,t')} = 1$ and $I_{(i,s')(j,t')} = 1$. $\alpha_{(i,sm)}(j,t) = \text{MIN}(\alpha_{(i,s)(j,t')}, \alpha_{(i,s')(j,t')})$, then

$$X_\lambda^{i,sm} + X_\lambda^{j,t'} \leq 1 \quad 1 \leq i, j \leq N(N-1), 1 \leq \lambda \leq W \quad (14)$$

Constraint for backup multiplexing rule 6 in Section II-B: if $I_{(i,s)(j,n)} = 0$, $I_{(i,s')(j,n)} = 0$, $I_{(i,m)(j,t)} = 0$, $I_{(i,m)(j,t')} = 0$, $I_{(i,s)(j,t')} = 1$, $I_{(i,s)(j,t)} = 1$, $I_{(i,s)(j,t')} = 1$, $I_{(i,s')(j,t)} = 1$ and $I_{(i,s')(j,t')} = 1$, $\alpha_{(i,sm)}(j,tmin) = \text{MIN}(\alpha_{(i,s)(j,t)}, \alpha_{(i,s)(j,t')}, \alpha_{(i,s')(j,t)}, \alpha_{(i,s')(j,t')})$, then

$$X_\lambda^{i,sm} + X_\lambda^{j,tmin} \leq 1 \quad 1 \leq i < j \leq N(N-1), 1 \leq \lambda \leq W \quad (15)$$

For following constraint, let $m, n \in \{0, 1, 2\}$; $s, s' \in \{m+1, m+2\}$, $s \neq s'$; $t, t' \in \{n+1, n+2\}$, $t \neq t'$. Constraint for rule 7: if $I_{(i,m)(j,n)} = 1$, $I_{(i,s)(j,t)} = 1$ and $I_{(i,s')(j,t')} = 1$, then

$$X_\lambda^{i,s'} + X_\lambda^{j,t'} \leq 1 \quad 1 \leq i, j \leq N(N-1), 1 \leq \lambda \leq W \quad (16)$$

IV. RESULTS AND DISCUSSION

We use CPLEX Linear Optimizer 5.0.1 to solve the ILPs. We first demonstrate the working of the ILPs using a small example. Then we present the numerical results for randomly generated demand matrices on a 11-node network.

A. An Illustration

Consider the simple 5-node network of Figure 1 again. Assume that the network has one fiber per link and 3 wavelengths per fiber. Let all node pair (i, j) be numbered sequentially in the order of i and j , i.e. node pair $(1, 2)$ is numbered 1, node pair $(1, 3)$ is numbered 2, and so on. Assume that each of four node pairs 1 $(1,2)$, 5 $(2,1)$, 13 $(4,1)$, 20 $(5,4)$ have one lightpath request between them. The routes and wavelengths of primary and backup lightpaths for the dedicated-path protection (as solved by ILP1), and the shared-path protection (as solved by ILP2) are given in Table II.

TABLE II

THE ROUTES AND WAVELENGTHS OF PRIMARY AND BACKUP PATHS UNDER DEDICATED- AND SHARED-PATH PROTECTION

Scheme	Node pair	Primary lightpath	Backup 1	Backup 2
Dedicated	1	$(1,2) \rightarrow \lambda_3$	$(1,3,2) \rightarrow \lambda_2$	$(1,5,4,2) \rightarrow \lambda_2$
	5	$(2,1) \rightarrow \lambda_3$	$(2,3,1) \rightarrow \lambda_1$	$(2,4,5,1) \rightarrow \lambda_3$
	13	$(4,2,1) \rightarrow \lambda_1$	$(4,3,1) \rightarrow \lambda_2$	$(4,5,1) \rightarrow \lambda_2$
	20	$(5,4) \rightarrow \lambda_3$	$(5,3,4) \rightarrow \lambda_3$	$(5,1,2,4) \rightarrow \lambda_1$
Shared	1	$(1,3,2) \rightarrow \lambda_3$	$(1,2) \rightarrow \lambda_3$	$(1,5,4,2) \rightarrow \lambda_1$
	5	$(2,3,1) \rightarrow \lambda_3$	$(2,1) \rightarrow \lambda_3$	$(2,4,5,1) \rightarrow \lambda_3$
	13	$(4,5,1) \rightarrow \lambda_2$	$(4,2,1) \rightarrow \lambda_1$	$(4,3,1) \rightarrow \lambda_1$
	20	$(5,3,4) \rightarrow \lambda_3$	$(5,4) \rightarrow \lambda_1$	$(5,1,2,4) \rightarrow \lambda_3$

In dedicated scheme, each reserved wavelength on a backup path is dedicated to a primary path. In contrast, in shared scheme, λ_3 on links $(5,1)$ and $(2,4)$ is shared by backup paths $2 \rightarrow 4 \rightarrow 5 \rightarrow 1$ and $5 \rightarrow 1 \rightarrow 2 \rightarrow 4$. λ_1 on links $(5,4)$ is shared by backup paths $1 \rightarrow 5 \rightarrow 4 \rightarrow 2$ and $5 \rightarrow 4$. λ_1 on links $(4,2)$ is shared by backup paths $4 \rightarrow 2 \rightarrow 1$ and $1 \rightarrow 5 \rightarrow 4 \rightarrow 2$. λ_3 on link $(1,2)$ is shared by backup paths $1 \rightarrow 2$ and $5 \rightarrow 1 \rightarrow 2 \rightarrow 4$. As stated in section II-B, backup paths $2 \rightarrow 1$ and $4 \rightarrow 2 \rightarrow 1$ can not share backup capacity on their common link $(2,1)$ because of backup multiplexing constraint 3 in Table I. The routings for the primary paths under dedicated- and shared-path schemes are different, because the routing under the shared-path scheme yields maximum saving for total capacity. The shared- and dedicated-path protection schemes use a total of 19 and 24 wavelength-links for this demand matrix, respectively. The shared-path protection saves about 21% capacity. In link-based protection, dedicated- and shared-link schemes use 28 and 23 wavelength-links, respectively[8].

B. Results on Modified NJ LATA Network

We present our solution on a modified NJ LATA network shown in Figure 2. The modifications include adding links $(1,4)$ and $(4,6)$, so that the network becomes three connected. We assume the network has one fiber per link for all optimizations. Three groups of demand sets were generated randomly. Each group consists of 10 sets of demand matrix. We wrote a program to generate each set of demand matrix using the following steps. Let TNR denotes the desired total number of requests, and let MNR denotes the maximum number of requests for any node pair.

1) counter = 0;

2) randomly generate source and destination nodes, and the number of requests for this node pair d_i , which is between 1 and MNR ;

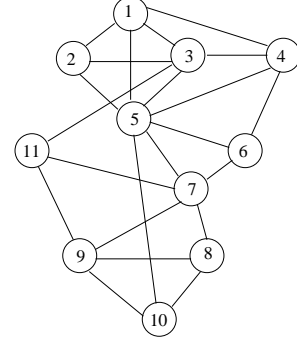


Fig. 2. A 11-node 22-link modified NJ LATA network

3) counter = counter + d_i ;

4) if counter < TNR , go to step 2;

The TNR for group I, II and III are 40, 60, 100, respectively. The MNR is 4 for group I, II and III. Assume the number of wavelengths per fiber is always sufficient to obtain the feasible solution for each scheme. The optimization results for group I, II and III are shown in Table III, IV and V, respectively. To study the effect of distribution of connection requests, we generated group IV by setting TNR and MNR to be 60 and 8, respectively. The optimization results for group IV are shown in Table VI. In all tables, we denote wavelength-links by WLS, dedicated-path protection scheme by DPS, and shared-path protection scheme by SPS.

TABLE III

THE OPTIMIZATION RESULTS FOR REQUEST GROUP I

set	number of node pairs	Total requests	WLS used by SPS	WLS used by DPS	Saving	Primary by SPS	Primary by DPS
1	16	41	213	288	26.0	82	59
2	22	41	218	310	29.7	78	68
3	14	40	237	307	22.8	80	75
4	17	40	240	322	25.5	83	77
5	19	40	220	314	24.3	82	65
6	17	42	224	314	23.3	84	73
7	12	41	234	320	26.9	79	67
8	16	41	282	363	22.3	103	86
9	22	40	227	341	33.4	90	83
10	17	41	241	321	24.9	94	80
				average	27.0		

Table III shows that for a total of about 40 requests the shared-path scheme requires between 22.3 - 33.4% smaller total capacity than dedicated-path scheme. For a total of about 60 connection requests, Table IV shows that the shared-path scheme saves between 26.7 - 34.3% of the total capacity. For a total of about 100 requests, shared-path scheme saves between 27.0 - 37.5% of the total capacity, as shown in Table V. We calculated the capacity used by primary paths for group II, shown in columns 7 and 8 of Table III. Results show that the average primary capacity for shared-path scheme is 14% higher than the average primary capacity for the dedicated-path scheme. This is due to the factor that in order to yield more

saving by sharing backup capacity, sometimes the shared-path scheme uses a longer primary path than the dedicated-path scheme.

TABLE IV
THE OPTIMIZATION RESULTS FOR REQUEST GROUP II

set	number of node pairs	Total requests	WLS used by SPS	WLS used by DPS	Saving
1	26	61	285	429	33.5
2	25	62	318	461	31
3	28	63	363	533	31.9
4	26	60	308	469	34.3
5	21	60	356	486	26.7
6	29	61	379	526	27.9
7	26	60	319	460	30.6
8	24	61	347	480	27.7
9	25	61	338	480	29.6
10	21	62	382	521	26.7
			average		29.93

TABLE V
THE OPTIMIZATION RESULTS FOR REQUEST GROUP III

set	number of node pairs	Total requests	WLS used by SPS	WLS used by DPS	Saving
1	43	100	456	729	37.5
2	44	101	521	803	35.1
3	37	100	541	818	33.9
4	48	101	546	798	31.6
5	41	101	555	805	31.0
6	38	102	559	818	31.7
7	36	102	571	823	30.6
8	48	103	562	827	32.0
9	36	101	492	739	33.4
10	38	101	607	833	27.0
			average		32.3

TABLE VI
THE OPTIMIZATION RESULTS FOR REQUEST GROUP IV

request set	number of node pairs	Total requests	WLS used by SPS	WLS used by DPS	Saving
1	14	65	342	436	21.55
2	15	65	359	499	28.0
3	13	62	385	489	21.3
4	14	62	383	470	18.5
5	16	60	380	507	25.0
6	13	60	378	501	24.5
7	12	64	355	449	20.9
8	16	67	402	548	26.6
9	14	63	415	493	15.8
10	14	60	402	544	26.1
			average		23.0

Among groups I to III, The group III obtains the most average saving and group I gets the least average saving in the total capacity. This is due to the fact that the number of node pairs in the demand matrix increases from group I to III as TNR increases from group I to III. This leads to more sharing in backup capacity. The group II gets more average saving than group IV, which has same number of TNR , but smaller number of node pairs compared to group II. This suggests that the demand matrix with connection requests distributed more evenly (as in the case in group III) will have more chances to share backup capacity, thus saves more in total capacity.

We conducted optimization for group I, with both dedicated- and shared-link methods presented in [8]. The results are summarized in Table VII (SLS:shared-link scheme;

DLS:dedicated-link scheme). Comparison between the results in Table III and Table VII shows that the path-based methods are more efficient in the total capacity utilization than the link-based methods, and on average, the dedicated-path scheme yields better performance than share-link scheme. There are no feasible solutions for some of the demand matrices in dedicated-link scheme. It is due to the fact that in the link-based methods, the backup paths have to use the same wavelength as the primary paths and in the dedicated-link scheme, it is easy for conflicts to occur between the two backup paths for the two links on the same primary path.

TABLE VII
THE OPTIMIZATION RESULTS FOR REQUEST GROUP I

request set	number of node pairs	Total requests	WLS used by SLS	WLS used by DLS	Saving
1	16	41	301	349	13.8
2	22	41	344	infeasible	NA
3	14	40	364	infeasible	NA
4	17	40	371	infeasible	NA
5	19	40	328	infeasible	NA
6	17	42	360	infeasible	NA
7	12	41	320	393	18.6
8	16	41	416	infeasible	NA
9	22	40	439	infeasible	NA
10	17	41	397	452	12.2

V. CONCLUSION

We presented a path-based double-link failure recovery model, in which two backup paths are provided for each node pair and resources are reserved for each connection. We developed the rules for identifying the scenarios when backup paths can share their backup capacity without violating 100% restoration guarantee. The shared-path scheme provides significant total capacity saving (up to 37.5%). We also found that the backup multiplexing provides more saving for the demand sets that distribute the connection requests more evenly. For the double-link failure recovery methods, path-based methods are more efficient in total capacity utilization than link-based methods. Dedicated-path scheme performs better than shared-link scheme in total capacity utilization on average.

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