

Enabling Subwavelength Level Traffic Grooming in Survivable WDM Optical Network Design

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Abstract—The explosion of data traffic and the availability of huge bandwidth using WDM optical network make it important to study optical layer networking restoration design. This paper addresses problem of enabling traffic grooming in mesh survivable WDM optical network design. Traffic grooming in optical network is defined as the act of multiplexing, demultiplexing and switching lower rate traffic onto high capacity lightpaths. The path selection and wavelength assignment schemes are formulated as integer linear programming (ILP) optimization problems. Two exact formulations are given for employing backup multiplexing and dedicated backup reservation with minimizing the total link-primary-sharing.

I. INTRODUCTION

Wavelength division multiplexing (WDM) is emerging as a dominant technology for use in backbone networks. WDM significantly increases the capacity of a fiber by allowing simultaneous transmission of multiple wavelengths (channels), each operating at rates up to 10Gb/s. There are several critical issues involved in using WDM optical networks effectively. We address two issues of current interest here.

First, due to the high bandwidth involved, any link failure that leaves fiber unusable will have catastrophic results. Thus protection and restoration schemes for the interrupted services must form an integral part of the network design and operation strategies. Although network survivability can be achieved at the higher layers above the optical layer, e.g., self-healing in SONET rings, and ATM virtual path layer, fast rerouting in MPLS and changing routes using dynamic routing protocols in the IP layer, it is advantageous to use optical WDM survivability mechanisms since they offer a common and fast survivability platform for services to the higher layers. Moreover, due to the availability of multiple paths on the same fiber, the higher layers may not be aware of and plan to use the same fiber as alternate path, obviously that will not work.

Next, the bandwidth on a wavelength is close to the peak electronic transmission speed and has been steadily increased from OC-48 (2.5 Gbps) to OC-192 (10Gbps), and is expected to increase up to OC-768 (40 Gbps). The bandwidth on a wavelength capacity is becoming too large for certain traffic requirements. Several sort of further traffic multiplexing on a wavelength is thus proposed [1], [2], [3]. One approach to pro-

visioning fractional wavelength capacity is to multiplex traffic on the wavelength. The resulting networks are referred to as WDM grooming networks. The aim of this research is to enable grooming capability in the design of survivable WDM mesh networks.

A. Survivable WDM Grooming Networks

WDM grooming network can be classified into two categories [5]: dedicated-wavelength grooming (DWG) networks and shared-wavelength grooming (SWG) networks. In DWG network, the source-destination node pairs (*s-d pairs*) are connected by lightpaths, where a lightpath is shared by requests from a specific s-d pair. In SWG network the lightpath can be shared by requests from different s-d pairs. The performance of SWG networks depend on the efficient merging of fractional wavelength requirements into full or almost-full wavelength requirements.

The grooming nodes in WDM networks can be classified into various categories depending on the level of grooming capability it provides. If a node can multiplex and demultiplex low-rate traffic only on *dropped* wavelengths at an add-drop multiplexer (ADM), it is referred to as a *ADM-constrained grooming node*. If a node can switch connections across different lightpaths, but cannot switch between different wavelengths, it is termed as a *wavelength continuity constrained grooming node*. If a node can switch connections in any permutation from one wavelength to another, it is then termed as a *full grooming node* [4].

Network survivability can be achieved by using link-, path- or segment based protection mechanism. Link-based method reroute disrupted traffic around the failed link, while path-based rerouting replaces the whole path between the source and destination of a demand. Segment-based method reroutes the affected path-segments when failure occurs. 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 have the same backup paths as long as the primaries are node and link disjoint. This scheme is called the backup multiplexing technique [9].

This paper deals with lightpath protection schemes for sub-wavelength level traffic grooming networks, which are defined as shared-wavelength grooming networks with wave-

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length continuity constrained grooming nodes. The paper is organized as follows: the remainder of Section I reviews prior work on survivable WDM network design. The ILP formulations for enabling grooming in survivable WDM network are presented in Section II. Results of ILP formulations are given in Section III. Section IV presents our concludes.

B. Related Work

Joint working (primary) and spare (backup) capacity planning in mesh-survivable WDM networks design has gained a lot of attention in optical community [6],[7], [8], [10]. An extensive review is omitted due to the space limitation.

Most of the proposed algorithms were designed for a network scenario where the full wavelength was the minimum unit of the bandwidth on a link. Hence they cannot be directly utilized in survivable grooming WDM network design. We deal with lightpath protection schemes for WDM networks with grooming capabilities and with given traffic that consists of low-rate traffic. Specifically, our solutions provide 100% guarantee protection under any single-link failure at the optical network layer using (1:1) optical path protection. To the best of our knowledge, there has been very limited research done in this area.

The study in [11] addressed the problem of dynamically establishing dependable low-rate traffic stream connections in WDM mesh networks with traffic grooming capabilities. To establish a dependable connection, they pre-computed link-disjoint primary and backup paths between the source and destination node and use backup multiplexing to reduce the overhead of backup traffic streams. Two schemes for grooming traffic streams onto wavelengths are proposed, namely *Mixed Primary-Backup Grooming Policy* (MGP) and *Segregated Primary-Backup Grooming Policy* (SGP). Their simulation results showed that SGP performs better in mesh networks and MGP performs better in ring networks. Similar study in the context of IP/MPLS protection/restoration with dynamic traffic has been done in [12], where k-shortest paths are pre-computed for each request and wavelength assignment followed the first-fit (FF) policy. The authors also applied backup multiplexing technique to reduce the redundant reserved spare capacity. Benefits gained by dynamically provisioning low-rate traffic streams at the IP/MPLS layer in IP over WDM optical networks are shown through simulations.

The above studies are both based on simulations. We investigate the problem of how to *groom* subwavelength level requests efficiently in mesh restorable WDM networks, and formulate the corresponding path selection and wavelength assignment problem as ILP optimization problems.

II. FORMULATION OF THE OPTIMIZATION PROBLEM

A. Restoration Model

We consider 100% restoration guarantee for any single link failure for protected connections. This implies that the primary (working) paths and the restoration (backup) paths are

assigned the same capacity and are link disjoint, given that it is possible in the network topology.

A.1 Backup multiplexing

One efficient way of assigning backup capacities is to employ *backup multiplexing* technique to improve the network resource utilization. This technique allows many restoration paths, belonging to different source-destination node pair, to share a wavelength w on a link (i, j) if and only if their corresponding primary paths are link and node disjoint. This is based on the fact that a single link failure will not break down two link disjoint paths.

In grooming WDM networks, the capacity reserved for restoration paths is more complicated. Let $B = \{b_1, b_2, \dots, b_k\}$ denotes the set of backup paths that traverse the wavelength w on link (i, j) . Let their respective capacities be $D = \{d_1, d_2, \dots, d_k\}$, and their respective primary paths be $P = \{p_1, p_2, \dots, p_k\}$. If none of the p_i 's have common link or node, the reserved capacity on w is $\max(d_1, d_2, \dots, d_k)$. If some of the p_i 's have common links or nodes, their backup paths can still be groomed on wavelength w . However, the capacity to be reserved may be up to the summation of their capacities. The primary paths can be grouped according to their common links. Let $P^l = \{p_1^l, p_2^l, \dots, p_a^l\}$ denote the group of primary paths that have link l as their common link. The capacity required by this group for back up of link l is then given by $D^l = (d_1^l + d_2^l + \dots + d_a^l)$. It is possible that one primary path belongs to more than one group. The reserved capacity on wavelength w on link (i, j) is therefore the maximum value of the capacities required by all the groups, that is $D = \max(D^l)$.

A.2 Dedicated backup reservation

Another simple and effective way of assigning backup capacities is to reserve dedicated capacity for each backup path. While choosing primary paths, instead of simply choosing the shortest path, we try to *minimize* the total *link-primary-sharing* (MLPS). The link-primary-sharing is defined as following,

$$s_{ij} = \max(0, P_{ij} - 1) \quad (1)$$

where s_{ij} denotes the link-primary-sharing of link (i, j) and P_{ij} denotes the total number of primary paths that utilize link (i, j) . s_{ij} can be viewed as the penalty assigned to link (i, j) when it is used by more than one primary path.

Backup multiplexing as well as dedicated backup reservation schemes with MLPS have been formulated in ILP optimization problems in Section II-D and II-E respectively.

B. Assumptions

The grooming survivable network design problem in a WDM mesh network with static traffic pattern is formulated into an ILP problem. We make the following assumptions.

1. The network is a single-fiber irregular mesh network.

2. A connection request cannot be divided into several lower speed connection requests and routed separated from the source to the destination. The data traffic on a connection request should always follow the same route.
3. The transceivers in a network node are fixed, hence wavelength continuity constraint still applies.
4. Each grooming node has unlimited multiplexing and demultiplexing capability. This means that the network node can multiplex/demultiplex as many low-speed traffic streams to a lightpath as needed, as long as the aggregated traffic does not exceed the lightpath capacity.

C. Notation

Given:

1. A physical topology $G_p = (V, E)$ consisting of a weighted unidirectional graph, where V is the set of network nodes and E is the set of physical links (edges). Nodes correspond to network nodes and links correspond to the fibers between nodes.
2. The number of nodes in the network is N , number of wavelengths carried by each fiber is W , capacity of each wavelength is C (assuming each wavelength has the same capacity). Here we use $C=OC-48$.
3. Traffic matrix $D_{N \times N} = \{d_m\}$, where d_m indicates the required capacity of low-speed traffic requests in units of OC-1. Here we chose $d_m=\{OC-1, OC-3, OC-12\}$.
4. Capacity weight of link (i, j) , denoted by c_{ij} , which is a positive real number and can be regarded as a measure of capacity consumption per wavelength on the link. These weights are used to differentiate links from the capacity cost point of view, for example, by link distance.

The following notations are used to describe various entities.

- $i, j = 1, 2, \dots, N$: Number assigned to each node in the network.
- $m, n = 1, 2, \dots, N \times (N - 1)$: Number assigned to each demand (s-d pair). Let s_m and t_m be the source and the destination node of demand m , respectively.
- $w = 1, 2, \dots, W$: Number assigned to each wavelength.
- $K = 2$: Number of alternate routes between every s-d pair.
- $p, r = 1, 2, \dots, KW$: 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 $1 \leq p, r \leq W$ paths belong to route 1 and $W + 1 \leq p, r \leq 2W$ paths belong to route 2.
- $\bar{p}, \bar{r} = 1, 2, \dots, KW$: if $1 \leq p, r \leq W$ (route 1), then $W + 1 \leq \bar{p}, \bar{r} \leq 2W$ (route 2) and vice versa

The following information is given regarding link usage and whether two given paths are link and node disjoint.

- $I_{(m,p),(n,r)}$: Takes a value of one if paths (m, p) and (n, r) have at least one link in common; zero otherwise. If two routes share a link, then all lightpaths using those routes have the corresponding I value set to one; else zero. (data).

The following notations are for path-related information.

- $\delta^{m,p}$: Path indicator that takes a value of one if (m, p) is chosen as a primary path; zero otherwise (binary variable).
- $\gamma^{m,r}$: Path indicator that takes a value of one if (m, r) is chosen as a restoration path; zero otherwise (binary variable).
- $\epsilon_{ij}^{m,p}$: Link indicator that takes a value of one if link (i, j) is used in path (m, p) ; zero otherwise (data).
- $\psi_w^{m,p}$: Wavelength indicator that takes a value of one if wavelength w is used by the path (m, p) ; zero otherwise (data).

The following variables are used to present wavelength assignment in this grooming network.

- $p_{ij,w}^m$: binary variable, 1 if wavelength w on link (i, j) is used by primary path of demand m ; 0 otherwise.
- $r_{ij,w}^m$: binary variable, 1 if wavelength w on link (i, j) is used by backup path of demand m ; 0 otherwise.
- W_{ij} : nonnegative integer, total number of wavelengths required on link (i, j) .
- $M_{ij,w}$: nonnegative integer, total capacity assigned to primary paths on wavelength w on link (i, j) .
- $R_{ij,w}$: nonnegative integer, total capacity reserved for backup paths on wavelength w on link (i, j) .

D. ILP formulation I: Backup multiplexing

D.1 Objective:

Minimize the total wavelength links: Given a network topology and a set of point-to-point demands and their link disjoint primary and backup routes, assign the primary and backup routes in an optimal way that the total wavelength links is minimized.

For each link, c_{ij} (a positive integer) is the capacity weight for link (i, j) . It can be regarded as a measure of capacity consumption per wavelength on the link, so it can be used to differentiate links in terms of *capacity cost*. Here we choose $c_{ij} = 1$ then the objective is to minimize the total number of *wavelength - links*.

$$\min \sum_{(i,j) \in E} c_{ij} \times W_{ij} \quad (2)$$

D.2 Constraints:

1. On physical route variables:

A lightpath can carry traffic for a s-d pair only if it is in the physical route of this request.

$$p_{ij,w}^m = \sum_{p=1}^{KW} \delta^{m,p} \epsilon_{ij}^{m,p} \psi_w^{m,p} \quad (3)$$

$$r_{ij,w}^m = \sum_{r=1}^{KW} \gamma^{m,r} \epsilon_{ij}^{m,r} \psi_w^{m,r} \quad (4)$$

2. On path indicators:

One and only one path will be assigned as a primary(backup) path for each request.

$$\sum_{p=1}^{KW} \delta^{m,p} = 1 \quad (5)$$

$$\sum_{r=1}^{KW} \gamma^{m,r} = 1 \quad (6)$$

3. On topology diversity of primary and backup paths:

Primary and restoration paths of a given demand should be node and link disjoint.

$$\sum_{p=1}^W \delta^{m,p} = \sum_{r=W+1}^{KW} \gamma^{m,r} \quad (7)$$

$$\sum_{p=W+1}^{KW} \delta^{m,p} = \sum_{r=1}^W \gamma^{m,r} \quad (8)$$

4. On wavelength capacity variables:

Primary capacities are aggregated. For each wavelength, the sum of primary capacities and backup capacities should not exceed the total wavelength capacity.

$$M_{ij,w} = \sum_m d_m \times p_{ij,w}^m \quad (9)$$

$$M_{ij,w} + R_{ij,w} \leq C \quad (10)$$

5. On fiber capacity constraints:

The number of wavelengths used on a fiber should not exceed the total number of wavelengths carried by the fiber. Equations (12), (13), and (14) together set $u_{ij,w} = 1$, if $x_{ij,w} \geq 1$, and zero otherwise. $x_{ij,w}$ counts the number of primary and backup paths that use wavelength w on link (i, j) , and W_{ij} counts the number of wavelengths used on link (i, j) . Recall that we assume single-fiber networks here.

$$x_{ij,w} = \sum (r_{ij,w}^m + p_{ij,w}^m) \quad (11)$$

$$u_{ij,w} \leq x_{ij,w} \quad (12)$$

$$KN(N-1)u_{ij,w} \geq x_{ij,w} \quad (13)$$

$$u_{ij,w} \in \{0, 1\} \quad (14)$$

$$W_{ij} \geq \sum_w u_{ij,w} \quad (15)$$

$$W_{ij} \leq W \quad (16)$$

6. On backup multiplexing constraint:

The capacity reserved for backup paths on a link need to take the correlations between the corresponding primary paths into account. If the primary paths do not have common links, their backup paths can share the same wavelength on their common links, the reserved capacity will be the maximum requested capacity among them. Otherwise, the capacity for their backups on the same wavelength will also be aggregated. Recall $R_{ij,w}$ denotes the

capacity assigned to backup paths on wavelength w on link (i, j) , $R_{ij,w}$ is given as:

$$\begin{aligned} R_{ij,w} \geq & d_m \times \gamma^{m,p} \epsilon_{ij}^{m,p} \psi_w^{m,p} \\ & + \sum_{n \geq m} d_n \times \gamma^{n,p,m,p} \epsilon_{ij}^{n,p} \psi_w^{n,p} \times I_{(m,\bar{p}), (n,\bar{p})} \\ & + \sum_{n \geq m} d_n \times \gamma^{n,\bar{p},m,p} \epsilon_{ij}^{n,\bar{p}} \psi_w^{n,\bar{p}} \times I_{(m,p), (n,\bar{p})} \\ & + \sum_{n \geq m} d_n \times \gamma^{n,p,m,\bar{p}} \epsilon_{ij}^{n,p} \psi_w^{n,p} \times I_{(m,\bar{p}), (n,p)} \\ & + \sum_{n \geq m} d_n \times \gamma^{n,\bar{p},m,\bar{p}} \epsilon_{ij}^{n,\bar{p}} \psi_w^{n,\bar{p}} \times I_{(m,p), (n,p)} \end{aligned} \quad (17)$$

where $\gamma^{n,p,m,p}$ is a binary variable which takes value of one when $\gamma^{n,p} = 1$ and $\gamma^{m,p} = 1$. It is given by Equation (18), (19) and (20).

$$\gamma^{n,p,m,p} \geq \gamma^{n,p} + \gamma^{m,p} - 1 \quad (18)$$

$$\gamma^{n,p,m,p} \leq \gamma^{n,p} \quad (19)$$

$$\gamma^{n,p,m,p} \leq \gamma^{m,p} \quad (20)$$

E. ILP formulation II: Dedicated backup with MLPS

E.1 Objective:

Minimize the total wavelength-links as well as total link-primary-sharing: Let s_{ij} denote the link-primary-sharing on link (i, j) , r_{ij} be the weight of s_{ij} . Here we choose $c_{ij} = 1$ as it is in Section II-D and $r_{ij} = 3$. The objective function is hence give as:

$$\min \left(\sum_{(i,j) \in E} c_{ij} \times W_{ij} + r_{ij} \times s_{ij} \right). \quad (21)$$

E.2 Constraints:

Constraints 3-15 are still applicable, only the backup capacities are calculated in a different way.

7. On backup wavelength capacity variables:

Backup capacities are aggregated when dedicated backup reservation is applied.

$$R_{ij,w} = \sum_m d_m \times r_{ij,w}^m. \quad (22)$$

8. On link-primary-sharing:

Recall the definition of s_{ij} in Section II-A.2, s_{ij} is non-negative and given as following.

$$s_{ij} \geq \sum_m \sum_w p_{ij,w}^m - 1 \quad (23)$$

$$s_{ij} \leq \sum_m \sum_w p_{ij,w}^m \quad (24)$$

III. ILLUSTRATIVE NUMERICAL RESULTS

A. Experimental Design

This section presents numerical results of the ILP formulations given in Section II-D and II-E on physical topologies given in Figure 1(a) and (b).

The performance of grooming depends on the efficiency of *grooming* fractional wavelength traffic onto full or almost-full

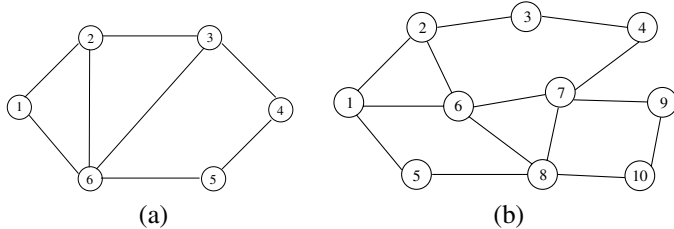


Fig. 1. Physical topologies used in experiments.

wavelength, hence, it also depends on the traffic pattern. When most of the traffic are of full-wavelength capacity or almost full-wavelength capacity, grooming will not bring much improvement on wavelength utilization. In this example traffic is randomly generated with each request having a capacity of OC-12, which is 1/4 of the full wavelength capacity. Two link disjoint alternate paths for each connection are pre-computed based on fixed shortest-paths routing algorithm.

We use CPLEX Linear Optimizer 7.0 [13] to solve the ILP formulation I and II. The experiments were run on a Pentium IV 1.80GHz processor with 526MB RAM. Tables I and II show the path selection and wavelength assignment results of the same set of requests on topology given by Figure 1(a) with ILP formulation I and II, respectively.

TABLE I
SOLUTION FROM ILP FORMULATION I

s-d pair	Formulation I			
	Primary		Backup	
1-3	1-2-3	w_3	1-6-3	w_2
1-4	1-2-3-4	w_3	1-6-5-4	w_2
1-5	1-2-3-4-5	w_3	1-6-5	w_2
2-4	2-3-4	w_2	2-6-5-4	w_4
2-5	2-6-5	w_4	2-3-4-5	w_3
2-6	2-6	w_4	2-1-6	w_2
3-5	3-4-5	w_3	3-6-5	w_4
3-6	3-2-6	w_4	3-6	w_4
4-2	4-3-2	w_4	4-5-6-2	w_2
4-5	4-3-6-5	w_4	4-5	w_2
5-2	5-6-2	w_2	5-4-3-2	w_4
5-3	5-4-3	w_4	5-6-3	w_2
6-1	6-2-1	w_2	6-1	w_1
6-3	6-3	w_2	6-2-3	w_2
6-4	6-3-4	w_2	6-5-4	w_2

Tables I and II shows that 21 wavelength-links are needed to carry all the 15 requests. The solution for the same request set in the network without traffic grooming capability can be obtained from formulation I as a special case where each request has full wavelength capacity. The results are shown in Table III. It turned out that minimum 52 wavelength-links are required in the network without traffic grooming capability.

From pre-computed path sets, we can calculate the maximum wavelength-links that are needed to establish all the primary and backup paths. Notice that without traffic grooming and backup multiplexing, 64 wavelength-links are needed, while backup multiplexing helps to reduce it to 52. The gain by

TABLE II
SOLUTION FROM ILP FORMULATION II

s-d pair	Formulation II			
	Primary		Backup	
1-3	1-2-3	w_3	1-6-3	w_3
1-4	1-6-5-4	w_3	1-2-3-4	w_3
1-5	1-6-5	w_3	1-2-3-4-5	w_3
2-4	2-3-4	w_2	2-6-5-4	w_1
2-5	2-6-5	w_1	2-3-4-5	w_2
2-6	2-6	w_1	2-1-6	w_3
3-5	3-4-5	w_2	3-6-5	w_1
3-6	3-6	w_1	3-2-6	w_1
4-2	4-3-2	w_1	4-5-6-2	w_3
4-5	4-5	w_2	4-3-6-5	w_1
5-2	5-6-2	w_3	5-4-3-2	w_1
5-3	5-6-3	w_3	5-4-3	w_1
6-1	6-1	w_1	6-2-1	w_3
6-3	6-3	w_3	6-2-3	w_3
6-4	6-5-4	w_3	6-3-4	w_3

TABLE III
SOLUTION WITHOUT TRAFFIC GROOMING

s-d pair	No Traffic Grooming			
	Primary		Backup	
1-3	1-2-3	w_6	1-6-3	w_6
1-4	1-2-3-4	w_3	1-6-5-4	w_1
1-5	1-6-5	w_3	1-2-3-4-5	w_2
2-4	2-3-4	w_4	2-6-5-4	w_7
2-5	2-6-5	w_2	2-3-4-5	w_7
2-6	2-6	w_8	2-1-6	w_2
3-5	3-6-5	w_8	3-4-5	w_5
3-6	3-6	w_6	3-2-6	w_7
4-2	4-3-2	w_6	4-5-6-2	w_2
4-5	4-5	w_4	4-3-6-5	w_7
5-2	5-6-2	w_4	5-4-3-2	w_7
5-3	5-6-3	w_5	5-4-3	w_1
6-1	6-1	w_3	6-2-1	w_2
6-3	6-3	w_4	6-2-3	w_2
6-4	6-5-4	w_5	6-3-4	w_6

using backup multiplexing is then 18.75%, and 8 wavelength-links are saved.

With subwavelength traffic grooming, 21 wavelength-links are sufficient, which means another 31 wavelength-links are saved. If we take the wavelength capacity granularity into account, the total required capacity is $64/4 = 16$ OC-12 capacity units. Without grooming, each lightpath uses full OC-48 capacity, although the requested capacity is OC-12, so totally 52 OC-48 capacity units have been occupied. With traffic grooming, although 21 wavelength-links have been used, it is still possible to pack other lightpaths on to some wavelengths even without taking backup multiplexing into account, because some wavelengths still have free bandwidth, and the total used capacity is exactly 16 OC-12 capacity units. This example clearly shows the improvement of capacity utilization by enabling subwavelength level grooming in the restorable WDM network design.

Although in the above example, backup multiplexing and dedicated backup with MLPS perform the same in terms of wavelength-links. This will not always happen. However in this scenario MLPS is preferred because fewer working paths

will be touched by single-link failures. For example, from Table I, the failure of link (2, 3) would affect 4 working paths in formulation I and 2 in formulation II as shown in Table II. Additionally, with the objective to minimize the total wavelength-links, backup multiplexing stops when the objective value does not decrease any more. It is still possible to reallocate some primary paths so that there could be more chances to multiplex backup paths onto some wavelength, and result in more spare capacity on the utilized wavelengths. But the value of the objective function will stay the same.

Different path selections can be observed from the Tables I and II. In order to simply minimize the total wavelength-links, grooming tends to exhaust one wavelength before using another wavelength. While link-primary-share is taken as a link penalty, in formulation II, it would be preferred to have more balanced load for primary paths.

We also performed experiments on the topology in Figure 1(b), which is a 10-node network with 14 bi-directional links. The randomly generated request matrix is shown in Table IV.

TABLE IV
REQUESTS MATRIX FOR THE 10-NODE-14-LINK NETWORK.

	1	2	3	4	5	6	7	8	9	10
1	0	0	0	12	1	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	12
3	0	3	0	0	0	0	0	0	0	0
4	0	0	0	0	3	1	0	3	12	0
5	0	0	0	0	0	0	0	0	1	0
6	0	0	3	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	3+1	0
8	1	0	12+12	0	0	0	1	0	0	0
9	0	3	0	0	12	3+3	0	0	0	0
10	3	0	0	0	0	0	0	0	0	0

The solution from formulation I shows that by employing backup multiplexing technique 28 wavelength-links are needed, while formulation II gives a solution requires 33 wavelength-links. In general, formulation II requires more wavelength-links in comparison to formulation I. However, this becomes affordable in networks with subwavelength grooming capability, where the wavelength utilization is significantly improved by traffic grooming. Moreover, from the respect of ILP formulation, formulation II has less complexity than formulation I in terms of number of constraints and variables, which makes formulation II less computationally expensive and hence more practical.

IV. SUMMARY

This paper addresses two important issues in WDM network design, survivability and traffic grooming. The aim is to enable subwavelength level traffic grooming in survivable WDM network design. In order to provide 100% protection under single link failure, two link-disjoint alternate paths for each connection are pre-computed. The path selection and wavelength assignment schemes are formulated as ILP optimization problems. Two exact formulations are given for employing backup

multiplexing and dedicated backup (with MLPS) respectively. Illustrative examples are given to show the improvement of wavelength utilization of the two schemes and the difference path selections.

Backup multiplexing, which has been extensively studied in mesh-restoration WDM networks, helps to make reduce the amount of spare capacity. It is still applicable in WDM grooming network, but it becomes much more computational expensive than it is in networks without grooming functionality. With the significantly improved wavelength utilization brought by grooming, it is affordable to use dedicated backup reservation to provide 100 % guaranteed restoration for single link failure. Furthermore, by minimizing the total link-primary-sharing, the number of affected working paths due to single link failure is reduced, such that the recovering signalling is simplified. It would be ideal to employ both backup multiplexing and MLPS scheme. However that will be too costly in computation and infeasible for practical usage.

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