Performance Evaluation of Survivable Multifiber WDM Networks[†]

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Abstract—**This article proposes a survivability evaluation model for multifiber WDM networks, in which the extended layered graph is developed to jointly optimize the wavelength routing and wavelength assignment problems, and three different edge cost functions are evaluated in terms of traffic engineering. Linear programming (LP) equations are formulated to optimally determine the working lightpath and the corresponding protection lightpath under the schemes of *shared protection* and *dedicated protection*. The extensive simulations show that *shared protection* with the *fiber and wavelength-based cost* function provides the best survivability.**

Keywords – multifiber WDM networks; layered graph; LP; survivalbility.

I. INTRODUCTION

By dynamically provisioning a tremendous amount of bandwidth with tens of terabits per second, wavelength division multiplexing (WDM) is playing a major role in the expansion of our networks. More bandwidth in each optical channel of WDM networks means more serious data loss each time when a fault occurs. This is why the survivability performance of WDM networks is an important research issue. A number of research results on survivable WDM networks have been reported in the literature. Modiano and Narula-Tam [1] proved that the survivability issue for WDM networks is NP-complete. Miyao and Saito [2] proposed the optimal design scheme for survivable WDM networks. The automatic protection switching (APS) function for survivable WDM networks is realized by *protection cycles* [3]. The availability analysis of the span-based recovery is presented in [4]. The implementation of span restoration and priority-based recovery assures that the WDM networks are survivable in the case of multiple failures.

There has been a recent interest in assessing the survivability performance improvement of multifiber WDM networks. This is motivated by the economic advantage of deploying bundles of fibers for the purpose of fault tolerance and network growth. In multifiber networks, each node includes a dynamically configurable optical switch that supports fiber switching and wavelength switching. Wavelength conversion is not a configured function, and thus the connection between two nodes must be assigned the same wavelength in all the intermediate edges. This is the so-called *wavelength continuity constraint*. A wavelength-routing node of nodal degree two (two input bundles and two output bundles), three fibers per bundle, and four wavelengths per fiber is depicted in Figure 1. Multifiber WDM networks are an alternative solution to overcome the *wavelength continuity constraint* [5], [6]. An *F*-fiber *W*-wavelength network is functionally equivalent to an *FW*-wavelength network with partial wavelength conversion of degree *F* [7]. The research in [8] shows that multifiber WDM networks actually increase wavelength utilization.

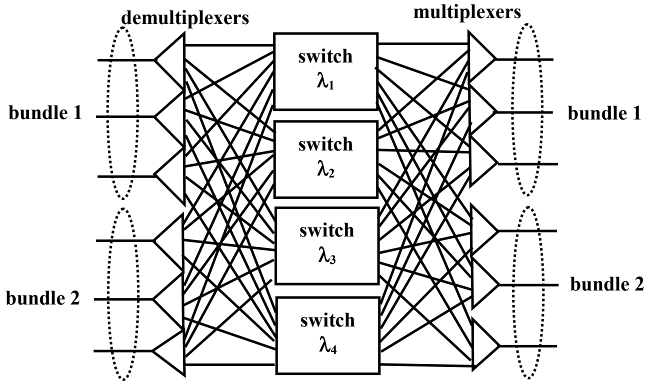

Figure 1. Wavelength node with degree 2, 3 fibers per link, and 4 wavelengths per fiber

In this paper, we focus on the survivability issue of multifiber WDM networks with the purpose of evaluating the survivability performance. We shall first define the following terms.

- **Multifiber network:** A network that utilizes multiple fibers in each link. Our study is focused on the even multifiber network, in which the number of fibers in each link is the same, and the number of wavelengths in each fiber is the same. An easy extension and the similar analysis can be applied to the uneven multifiber networks.
- **Link:** A bundle of fibers in the optical network between two nodes.
- **Lightpath:** An optical communication path between two nodes, established by allocating the same wavelength throughout the route of the transmission. There is no wavelength conversion in the intermediate nodes, and *wavelength continuity constraint* is applied on a lightpath.
- **Layered graph:** The virtual logical topology of a physical network. In a layered graph, each layer represents the same wavelength connections among the network nodes.

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- **Edge:** The connection between two nodes in the layered graph. An edge is an actual wavelength between two nodes.

The rest of the paper is organized as follows. The evaluation model for survivable multifiber WDM networks is proposed in Section II. Formulations for *shared protection* and for *dedicated protection* are derived by LP equations in Section III. The simulations and corresponding discussions are presented in Section IV. Conclusions are given in Section V.

II. THE EVALUATION MODEL

A network is survivable if any single link failure does not disconnect the traffic in the network. To achieve such survivability, a protection lightpath is assigned to a working lighpath. In the case of any intermediate link failure, the traffic is guaranteed by switching it into the protection lightpath. Disjoint protection lightpath is a desired recovery scheme, which resolves the worst case when all the intermediate links fail. The network survivability issue can be described as follows: given the network traffic matrix, the problem is to (a) find a lightpath as the working lightpath for each traffic, and (b) find a disjoint lightpath as the protection lightpath for each traffic. Selecting the working and corresponding protection lightpath is a *routing and wavelength assignment* (RWA) problem, which is NP-complete. In this section, a model with two components is developed to resolve the above survivability issue. The extended layered graph component supports the joint optimization of wavelength routing and wavelength assignment problems. The working lightpath and the disjoint protection lightpath can be easily selected in the extended layered graph, and wavelength continuity in each lightpath is guaranteed. The edge cost function component facilitates traffic admission and traffic engineering. By properly choosing the edge cost function, traffic load in each link could be balanced according to the network status information.

A. The Extended Layered Graph

Consider a graph $G(N, E, F, W)$ for a given multifiber WDM network, where N is the node set, $|N|$ is the total number of nodes; E is the link set, E_i represents the bi-directional link numbered i, $|E|$ is the total number of links; F is the number of fibers per link; W is the number of wavelengths per fiber.

The layered graph G_L can be obtained from a given graph G by the following procedure:

1) Replicate the given graph G for W times in G_L. Each layer represents the s^{th} wavelength, i.e., λ_s, $\lambda_s \in \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$.

2) In each layer, replicate link E_i for F times. Each edge in the layered graph denotes an actual wavelength connection in the network.

Figure 2 shows an example of an even 2-fiber 4-wavelength WDM network with nodes N_1, N_2, N_3, N_4 and links E_1, E_2, E_3, E_4 , E_5. Each link is a bundle of two fibers, and each fiber accommodates four wavelengths λ_1, λ_2, λ_3, λ_4. Figure 3 shows the layered graph of this network. We replicate the original graph four times, with the first layer for wavelength $\lambda_{1,}$ the second layer for $\lambda_{2,}$ the third layer for $\lambda_{3,}$ and the fourth layer for λ_4. In each layer, replicate each link twice as the edges in G_L. For example, the link E_2 in G is denoted as edges E_2^{st} (s=1, 2; t=1, 2, 3, 4) in the layered graph G_L, where s stands for the fiber number, and t for the wavelength number (e.g., link E_2 has two edges in layer three: E_2^{13} and E_2^{23}).

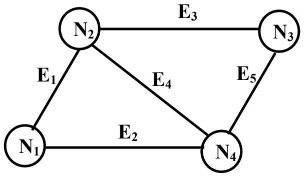

Fig. 2. Physical network

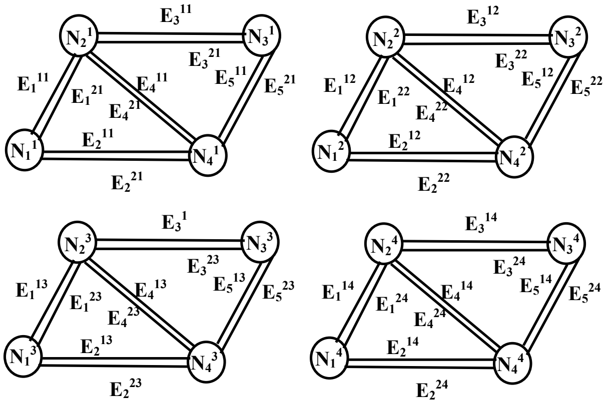

Fig. 3. Layered graph

In the layered graph, each route is one actual lightpath with wavelength continuity. By using such a route, there is no requirement for wavelength conversion. As a simple example, if we need to find a route for the node pair (N_1, N_3) with wavelength λ_2, we can set up such route by using the layer two in G_L. Instead of considering wavelength routing and wavelength assignment separately in G, the layered graph G_L provides a scheme to combine these two problems together. In the layered graph, whenever a route is found, its wavelength continuity is guaranteed. Therefore, the layered graph model tightly couples the wavelength routing and wavelength assignment steps together. It provides a framework for obtaining the exact optimal solution for the number of requested lightpaths as well as for the throughput that a given network can support. It is easy to see that if a set of working and protection lightpaths is found in the layered graph, then all of them can be supported in the corresponding physical network. If two lightpaths do not share the same link (one link has F fibers in each layer) and the same intermediate nodes (one node has one replication in each layer), they are disjoint in the physical network. Therefore, the network survivability issue can be reduced into the problem of finding a pair of disjoint lightpaths in the layered graph for each traffic.

B. The Edge Cost Function

A paramount concern of a survivable network is to ensure the end-to-end availability of lightpaths in the case of link failures with the least cost. The cost for traffic transmission is the sum of all the edge costs along the lightpath. The cost function of edges falls into one of two categories: *static cost*, where the edge cost is fixed without considering the network status, and *adaptive cost*, where the cost of an edge is updated by the network state information (e.g., available bandwidth).

For the static edge cost function, each edge's cost function is fixed, and there is not much difference between single fiber and multifiber networks. For the adaptive cost function, the edge cost function in multifiber networks is much more complex than in the single fiber networks. Instead of updating the cost function by wavelength availability information in single fiber networks, the cost function can be dynamically updated as a combination of the wavelength availability and fiber availability. We categorize the edge cost function in multifiber networks into the following three types:

1) ***Constant cost***: the cost function of edge E_i^{st}, i.e., $C(E_i^{st})$, is defined as follows:

$$C(E_i^{st}) = \begin{cases} \alpha_i^{st}, \text{ if } E_i^{st} \text{ is not occupied} \\ \infty, \text{ otherwise} \end{cases}, \tag{1}$$

where α_i^{st} is a constant for edge E_i^{st}. The cost function is fixed no matter what the network status is. When the edge is occupied, the edge cost is set to infinite to avoid future utilization.

2) ***Wavelength-based cost***: the cost is updated by the wavelength utilization information in a fiber, i.e.,

$$C(E_i^{st}) = \begin{cases} \alpha_i^{st} + \beta_i^{st} \dfrac{W_o}{W_t}, \text{ if } W_o < W_t \\ \infty, \text{ otherwise} \end{cases}, \tag{2}$$

where W_t is the total number of wavelengths in a specific fiber E_i^s, W_o is the number of occupied wavelengths in this fiber, and α_i^{st} and β_i^{st} are constant weight factors for edge E_i^{st}. The ratio $\beta_i^{st} / \alpha_i^{st}$ determines how much the edge cost depends on the available wavelength in one fiber. The cost will increase as the number of occupied wavelengths in a fiber increases. When all of the wavelengths are used up, the cost is infinite.

3) ***Fiber and wavelength-based cost***: the edge cost is updated by the combination of available wavelengths in a fiber and available fibers in a link, i.e.,

$$C(E_i^{st}) = \begin{cases} \alpha_i^{st} + \beta_i^{st} \dfrac{W_o}{W_t} + \gamma_i^{st} \dfrac{F_o}{F_t}, \text{ if } W_o < W_t \\ \infty, \text{ otherwise} \end{cases}, \tag{3}$$

where F_t is the total number of fibers in link E_i, F_o is the number of occupied fibers in link E_i (a fiber is occupied if at least one of its wavelengths is used), α_i^{st}, β_i^{st}, and γ_i^{st} are constant weight factors for edge E_i^{st}. The ratio $\beta_i^{st} / \alpha_i^{st}$ determines how much the edge cost depends on the available wavelength in one fiber, and the ratio $\gamma_i^{st} / \alpha_i^{st}$ determines how much the edge cost depends on the available fibers in one link. The cost will increase if more number of wavelengths are used or more number of fibers are occupied. This cost function takes consideration of the occupied wavelengths in a specific fiber E_i^s and the occupied fibers in a specific link E_i. When all of the wavelengths are occupied, the cost is infinite.

The *constant cost* strategy is a static one, in which the cost of each edge is fixed throughout the time. The *wavelength-based cost* is an adaptive one, which considers the influence of the number of occupied wavelengths in a fiber; it includes the local wavelength availability in one fiber. The *fiber and wavelength-based cost* is also an adaptive one with two dynamic factors: the number of occupied wavelengths in a specific fiber, and the number of occupied fibers in a specific link. This strategy is motivated by the common practice that in a bundle of fibers connecting two nodes, i.e., a link, the availability of one wavelength channel is decided by the unoccupied fibers in this link and the unoccupied wavelengths in the available fibers. If we use the least cost routing policy, the major difference between the constant and the adaptive cost function is that, under the *constant cost function*, some links are more often selected while others are relatively idle, while under the *wavelength-based cost* and the *fiber and wavelength-based cost*, the traffic will be allocated to the less congested links based on the network state information. In Section IV, we evaluate the performance of these three different cost functions.

III. NETWORK SURVIVABILITY PROBLEM FORMULATIONS

To survive link failures, one disjoint protection lightpath must be assigned to a specific working lightpath. The schemes to assign the protection lightpath can be categorized into two types: the *dedicated protection* lightpath, in which each working lightpath is protected by a disjoint protection lightpath (this protection lightpath is dedicated only to a specific working lightpath, and cannot be shared by other working lightpaths); the *shared protection* lightpath, in which the protection lightpaths can have common links.

A. Notations

For an even multifiber network $G(N, E, F, W)$, its corresponding layered graph is $G_L(N, E, F, W)$, node set is $N_L = \{N_1^1, N_1^2, ..., N_1^W, ..., N_n^1, N_n^2, ..., N_n^W\}$, edge set is $E_L = \{E_1^{11}, E_1^{12}, ..., E_1^{1W}, E_1^{21}, E_1^{22}, ..., E_1^{2W}, ..., E_e^{FW}\}$, $n=|N_L|$ is the total number of nodes, $e=|E_L|$ is the total number of links, F is the total number of fibers in each link, and W is the total number of wavelengths in each fiber. For the traffic matrix ***M***, we introduce the following notations:

$\{P_1, P_2, ..., P_M\}$:
the set of working lightpaths for traffic matrix M,

$\{\overline{P}_1, \overline{P}_2, ..., \overline{P}_M\}$:
the set of protection lightpaths for traffic matrix M,

$|P_a|$: the traffic in the working lightpath P_a,

$|\overline{P}_a|$: the traffic in the protection lightpath $\overline{P}_a$,

E_i : i^{th} link in $G(N,E,F,W)$,
E_i^s : s^{th} fiber in i^{th} link,
E_i^{st} : the edge in $G_L(N_L,E_L,F,W)$, i.e., t^{th} wavelength in s^{th} fiber of i^{th} link,

$C(E_i^{st})$: the cost of edge E_i^{st},
$C(P_a)$: the cost of lightpath P_a,

$$I^{P_a}_{E_i^{st}} = \begin{cases} 1, & \text{if working lightpath } P_a \text{ uses edge } E_i^{st} \\ 0, & \text{otherwise} \end{cases},$$

$$Q^{\overline{P}_a}_{E_i^{st}} = \begin{cases} 1, & \text{if protection lightpath } \overline{P}_a \text{ uses edge } E_i^{st} \\ 0, & \text{otherwise} \end{cases}.$$

B. LP Formulations

In the following formulations, we assume that each traffic in ***M*** requires one wavelength bandwidth. The *shared protection* scheme is then formulated as follows.
Minimize the cost:

$$\min\Big(\sum_{P_a=P_1}^{P_M} C(P_a) + \sum_{\overline{P}_a=\overline{P}_1}^{\overline{P}_M} C(\overline{P}_a)\Big), \tag{4}$$

where the working lightpath cost:

$$C(P_a) = \sum_{i=1}^{e}\sum_{s=1}^{F}\sum_{t=1}^{W} C(E_i^{st}) I^{P_a}_{E_i^{st}} \ , P_a \in \{P_1, P_2, ..., P_M\}, \tag{5}$$

the protection lightpath cost:

$$C(\overline{P}_a) = \sum_{i=1}^{e}\sum_{s=1}^{F}\sum_{t=1}^{W} C(E_i^{st}) Q^{\overline{P}_a}_{E_i^{st}} \ , \overline{P}_a \in \{\overline{P}_1, \overline{P}_2, ..., \overline{P}_M\}, \tag{6}$$

subject to the following constraints:
wavelength constraint:

$$\sum_{P_a=P_1}^{P_M}\sum_{t=1}^{W} I^{P_a}_{E_i^{st}} \le W \ , E_i^{st} \in E \ , s \in \{1,2,...,F\}, \tag{7}$$

bandwidth requirement constraint:

$$\sum_{P_a=P_1}^{P_M} I^{P_a}_{E_i^{st}} \le 1 \ , E_i^{st} \in E \ , \tag{8}$$

link capacity constraint:

$$\sum_{P_a=P_1}^{P_M}\sum_{s=1}^{F}\sum_{t=1}^{W} I^{P_a}_{E_i^{st}} \le FW \ , \tag{9}$$

traffic recovery constraint:

$$\sum_{P_a=P_1}^{P_M} | P_a | = \sum_{\overline{P}_a=\overline{P}_1}^{\overline{P}_M} | \overline{P}_a |, \tag{10}$$

disjoint protection constraint:

$$\sum_{s=1}^{F}\sum_{y=1}^{F}\sum_{t=1}^{W}\sum_{x=1}^{W} I^{P_a}_{E_i^{st}} Q^{\overline{P}_a}_{E_i^{xy}} = 0 \ , a \in \{1,2,...,M\}, i \in \{1,2,...,e\}. \tag{11}$$

For an *F*-fiber *W*-wavelength network, minimizing the total cost for the working lightpaths and the protection lightpaths is the objective of LP (4). The total cost is the sum of the cost for the working lightpaths (5) and the protection lightapsths (6). Each fiber E_i^s only accommodates at most *W* working lightpaths (7). Each working lightpath only requires at most one wavelength bandwidth (8). Constraint (9) limits the traffic load in a link; the total load of all the working lightpaths in a link cannot be larger than the link capacity of *FW* wavelengths. We consider 100% protection for each traffic (10) to avoid the serious data loss per failure. Full protection is realized by assigning disjoint protection lightpath for each working lightpath (11); no common links and no common intermediate nodes exist between the working lightpath and the corresponding protection lightpath.

The above equations are the formulation for the *shared protection* scheme. Protection lightpaths for different working lightpaths can be assigned common edges if possible. This *shared protection* can ensure survivability of any single failure in the network. In the case of multiple failures, the *dedicated protection* scheme must be deployed, and the following constraint are also required in addition to (4)-(11):

$$\sum_{\overline{P}_a=\overline{P}_1}^{\overline{P}_M} Q^{\overline{P}_a}_{E_i^{st}} \le 1 \ . \tag{12}$$

This inequality ensures that each edge at most accommodates one protection lightpath. The edges of one protection lightpath are not shared with other protection lightpaths.

IV. NUMERICAL RESULTS

Simulations are conducted on the NSFNET topology with three different fiber-wavelength combinations: 2-fiber 8-wavelength, 4-fiber 4-wavelength, and 8-fiber 2-wavelength. The traffic matrix has 55 connection requirements, and each requires a bandwidth of one wavelength and a protection lightpath. Four algorithms are implemented to compare their survivability performance. Algorithm I applies the the *constant cost function*. α_i^{st} in (1) is set to be 1. The lightpath is assigned by the *shortest path* scheme; a disjoint protection is dedicated for a working lightpath. Algorithm II implements the *wavelength-based cost function*, where α_i^{st} and β_i^{st} in (2) are both equal to 1. A dedicated least cost protection lightpath is assigned for a working lightpath. Algorithm III accommodates the *fiber and wavelength-based cost function*, where α_i^{st} , β_i^{st} and γ_i^{st} in (3) are all set to be 1, and the dedicated protection scheme is deployed. Algorithm IV is a shared protection version of algorithm III; it adopts the same edge cost function as Algorithm III except that the protection lightpath could share common edges if possible.

Table I (a)-(c) summarizes the survivability performance for each scenario. The unprotected solution decreases as the number of fibers increases. Increasing the number of fibers results in higher connectivity in the layered graph, and therefore less hop count for each lightpath. Among Algorithms I, II, and III, Algorithm I is the greediest one; it searches for the lightpath with the least hop, and thus the average hop count is the least. On the other hand, the network load for each fiber is seriously uneven for the shortest routing scheme, and this leads to more unprotected connections in Algorithm I. The shared protection allows Algorithm IV to protect more working traffic with less network resources, as compared with Algorithm III. However, the protection in Algorithm IV is only applicable to a single failure while the protections in other three algorithms are effective for multiple failures.

TABLE I. Survivabikity performance comparison

(a). 2-fiber 8-wavelength network

Algorithm	I	II	III	IV
Unprotected connection	3.0	3.0	3.0	0
Ave. lightpath hop	2.65	2.90	2.85	2.55

(b). 4-fiber 4-wavelength network

Algorithm	I	II	III	IV
Unprotected connection	2.0	2.0	1.0	0
Ave. lightpath hop	2.60	2.75	2.70	2.45

(c). 8-fiber 2-wavelength network

Algorithm	I	II	III	IV
Unprotected connection	1.0	0	0	0
Ave. lightpath hop	2.40	2.55	2.50	2.20

TABLE II. Network load distribution

(a). 2-fiber 8-wavelength network

	Algorithm I	Algorithm II	Algorithm III
Average	6.6 load/fiber	7.2 load/fiber	7 load/fiber
Standard deviation	1.50 load/fiber	1.16 load/fiber	0.82 load/fiber

(b). 4-fiber 4-wavelength network

	Algorithm I	Algorithm II	Algorithm III
Average	3.3 load/fiber	3.5 load/fiber	3.5 load/fiber
Standard deviation	0.85 load/fiber	0.66 load/fiber	0.62 load/fiber

(c). 8-fiber 2-wavelength network

	Algorithm I	Algorithm II	Algorithm III
Average	1.5 load/fiber	1.7 load/fiber	1.7 load/fiber
Standard deviation	0.75 load/fiber	0.58 load/fiber	0.49 load/fiber

Table II (a)-(c) illustrates the traffic distribution for each scenario. With the *constant cost function* and the *shortest path* routing, Algorithm I distributes the traffic load unevenly in each fiber. By taking consideration of the wavelength utilization of each fiber, Algorithm II reduces the traffic load standard deviation compared with Algorithm I. Algorithm III uses the global resource information, and this scheme generates the best load balancing result. When an incoming traffic arrives, Algorithm II routes it into the fiber with more available wavelengths, while Algorithm III routes it into the fiber with more available wavelengths, and this fiber is located in the link with more idle fibers. The *adaptive cost functions* (Algorithms II and III) are superior to the *constant cost function* (Algorithm I) in terms of the network load balancing. This is because, as the network traffic load increases, the *adaptive cost functions* tend to distribute the load to lightly loaded edges and avoid the heavily loaded ones. Between the two adaptive schemes, the *fiber and wavelength-based cost function* (Algorithm III) employs much more accurate global network state information, and therefore results in more evenly loaded traffic; the load variation among all edges is less.

V. CONCLUSIONS

The common practice of installing bundles of multiple fibers motivates the recent research on the multifiber WDM networks. Multifiber WDM networks without wavelength conversion are attractive alternative for single fiber networks with wavelength conversion capability. In this paper, we address the survivability issue of multifiber networks with the purpose of protecting each working lightpath by a disjoint protection lightpath. To evaluate the survivability performance, the extended layered graph is proposed to jointly optimize the wavelength routing and wavelength assignment problems. Based on LP, the mathematical formulations for survivable multifiber networks are derived. *Shared protection* recovers the traffic from any single edge failure, while *dedicated protection* recovers multiple failures. To realize network traffic engineering, different edge cost functions are proposed. Our extensive simulations verify that the *fiber and wavelength-based cost* function results in marginal improvements in the load balancing distribution, because it incorporates more network state information about fiber utilization and wavelength utilization.

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