Sub-Path Protection for Scalability and Fast Recovery in WDM Mesh Networks[1]

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Abstract: We investigate the advantages of partitioning a WDM mesh network to support modified shared-path protection, called sub-path protection. By fragmenting a lightpath into sub-paths spanning multiple areas, scalability and fault-recovery time are significantly improved.

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1 Introduction

In an optical wavelength-division multiplexing (WDM) network, the failure of a network element (e.g., fiber link, cross-connect, etc.) can cause the failure of several optical channels, thereby leading to large data (and revenue) loss [1]. A significant amount of work has been done to provide protection switching in ring topologies. As networks migrate from stacked rings to meshes because of the excessive resource redundancy used in ring-based protection, mesh-structured protection schemes have been receiving increasing attention [2, 3, 4, 5]. The work in [2] decomposes a mesh topology into protection cycles, which then perform automatic protection switching (APS). The work in [3] addresses mesh-structured protection by dividing a given working path into overlapped segments while protecting each segment separately. It, however, works on a per-working-path basis and computes working paths completely prior to backup paths.

We propose a variation of shared-path protection [5], called sub-path protection, which minimizes the total resource usage (in terms of wavelength-links), for a given traffic demand and area partitioning, while *guaranteeing* fast recovery time.

2 Sub-Path Protection

The main ideas of sub-path protection are (1) to partition a large network into several smaller areas as done by the open shortest path first (OSPF) routing algorithm, and then (2) to jointly compute two fiber-disjoint paths, p_w and p_b, for a given connection request d such that p_w and p_b enter (or exit) an area from the same ingress (or egress) area border router (ABR) if d is an inter-area connection, and they stay in the same area if d is an intra-area connection.

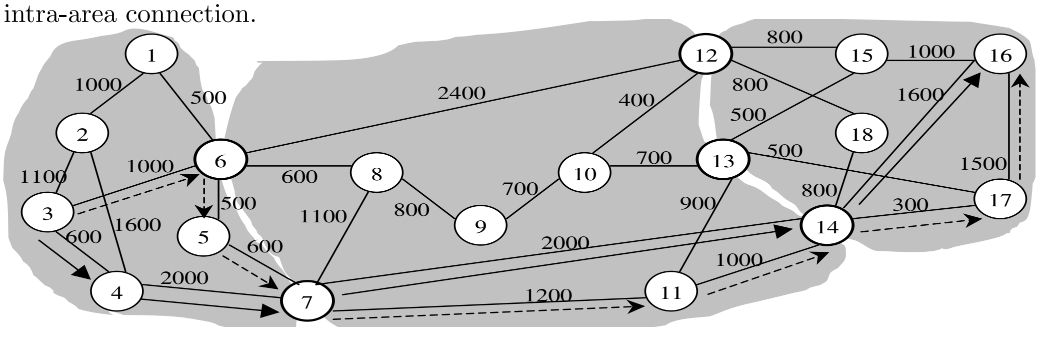

Fig. 1. An example 18-node nationwide network where each cloud denotes an area. Area 1 includes nodes $1 \sim 7$ and the links in between (if there is a link between two ABRs of two areas, the link belongs to one area only); Area 2 includes nodes $6 \sim 14$ and the links in between; Area 3 includes nodes $12 \sim 18$ and the links in between. Nodes 6, 7, 12, 13, and 14 are ABRs. The number besides each link is the length of the link. The solid (dotted) arrows form the working (backup) path between node-pair $(3, 16)$.

Consider an inter-area connection between node-pair $(3, 16)$, as shown in Fig. 1. The working path, p_w, is $< 3, 4, 7, 14, 16 >$, and the backup path, p_b, is $< 3, 6, 5, 7, 11, 14, 17, 16 >$. Note that p_w and p_b exit Area 1 (and enter Area 2) from the same ABR 7 and exit Area 2 (and enter Area 3) from the same ABR 14. ABRs 7 and 14 segment p_w and p_b into three sub-paths, respectively, $< 3, 4, 7 >$ (p_{w_1}), $< 7, 14 >$ (p_{w_2}), and $< 14, 16 >$ (p_{w_3}) for p_w; $< 3, 6, 5, 7 >$ (p_{b_1}), $< 7, 11, 14 >$ (p_{b_2}), and $< 14, 17, 16 >$ (p_{b_3}) for p_b. Each (p_{w_i}, p_{b_i})

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[1] This work was done when Canhui worked at Sprint Advanced Technology Labs (Burlingame, CA) as a summer intern.

pair corresponds to the working and backup paths of some intra-area traffic. When fiber link $< i, j >$ (e.g., $< 7, 11 >$) along p_w fails, instead of shutting down the entire working path p_w and switching the traffic to p_b, our proposed scheme only turns down the sub-path p_{w_k} (p_{w_2}) that traverses the failed link, and switches the traffic to p_{b_k} (p_{b_2}). As a result, other sub-paths (p_{w_1} and p_{w_3}) that do not traverse fiber link $< i, j >$ are not affected. Because of the independence of sub-paths, *sub-path protection can survive from up to A failures as long as there is at most one failure per area, where A is the number of areas.*

Depending on the wavelength-conversion capability of ABRs, there are two cases of sub-path protection. In the absence of wavelength converters at ABRs (in which case we say that ABRs are wavelength continuous), for sub-path protection to work, the working and backup paths of inter-area traffic must be on the same wavelength. Suppose ABRs 7 and 14 are wavelength continuous. If p_{w_1} is on wavelength λ_1 and p_{b_2} is on λ_2, when link $< 7, 11 >$ fails, we cannot simply switch the traffic from p_{w_2} to p_{b_2} because p_{w_1} and p_{b_2} are on different wavelengths. If there are wavelength converters at ABRs, then each sub-path of one path can be on any wavelength, regardless of the wavelength assignments of other sub-paths of the same path.

3 Problem Statement

The routing and wavelength assignment (RWA) problem in a WDM mesh network with sub-path protection is formally stated as follows. Given a physical topology $G = (V, E)$ (where V is the set of network nodes and E is the set of fiber links), a partitioning configuration $\wp$ (where $\wp$ is a set of areas, and an area comprises a set of network nodes), the number of wavelengths on each fiber, and a static connection demand matrix, route each connection request on G and assign a wavelength to each sub-path such that the total network cost is minimized or the network throughput is maximized. We formulated the above problem as an integer liner program (ILP). Our objective is to minimize the total number of wavelength-links. Since an ILP that jointly computes routes and assigns wavelengths is computational intensive, we also developed an ILP for routing and an ILP for wavelength assignment. Due to space limitations, ILPs are not shown here.

4 Results and Discussions

We compare the scalability, recovery time, and resource utilization (number of wavelength-links) of sub-path protection with those of shared-path protection by applying the two-step ILPs to the network in Fig. 1. For our numerical examples reported here, the number of wavelengths on each link, W, ranges from 6 to 12, while the number of connection requests that need to be carried, denoted by D, ranges from 25 to 50.

4.1 *Scalability*

We consider scalability in terms of the number of constraints the ILPs have. Let $\psi(|E|, W, D)$ and $\psi'(|E|, W, D)$ be the number of constraints in shared-path and sub-path protection ILPs, respectively. It is a straightforward matter to show from our ILPs that $\psi(|E|, W, D) = \Theta(W \times |E|^2 + D \times |E|)$. Let A be the number of areas; D_0 be the number of intra-area connections; D_1 be the number of inter-area connections ($D_0 + D_1 = D$); H be the average number of areas that an inter-area connection traverses ($H < A$; H depends on D and the partitioning configuration $\wp$). Assume that the partitioning is uniform, i.e., each area has $\lceil |E|/A \rceil$ links; and traffic demand distribution is uniform, i.e., each area has $(D_0 + D_1 \times H)/A$ traffic demands. Then $\psi'(|E|, W, D) = A \times \psi(\lceil |E|/A \rceil, W, (D_0 + D_1 \times H)/A) = \psi(|E|, W, D_0 + D_1 \times H)/A$. Since H is small compared to A, $\psi'(|E|, W, D) \approx \psi(|E|, W, D)/\alpha$, where α is a scale factor, and $\alpha \approx A$. For the network shown in Fig. 1, our results indicate that $\alpha = 2.6$ ($A = 3$). As a result, computational complexity reduces significantly: The memory requirement of ILPs for sub-path protection is about 90% lower than that of ILPs for shared-path protection. The time to solve the ILPs for sub-path protection is less than one-tenth of the time needed to solve the ILPs for shared-path protection in the worst case ($W = 6, D = 25$), and the solution-time ratio decreases rapidly to 0.2% as D increases ($W = 8, D = 40$). Clearly, computational complexity will decrease drastically as the network size grows larger.

4.2 *Recovery Time*

The recovery time[2] of link $< i, j >$ with respect to a connection between node-pair (s, d), T_{ij}^{sd}, is defined as the period over which data on the (s, d) connection were lost due to the failure of link $< i, j >$. Let d_{is} be the propagation delay from node i to node s, h_{is} be the number of hops from node i to node s, and h_b be

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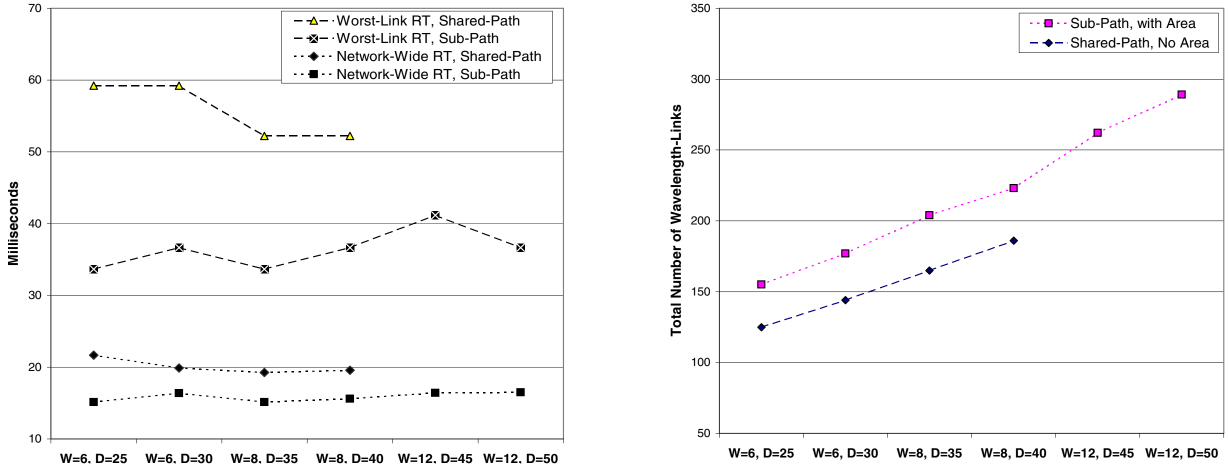
[2] Note that the recovery time here is similar to the protection-switching time defined in [5], but it has some improvements, e.g., parallelizing the switch configurations.

the number of hops on the backup path between node-pair (s, d). Assume failure detection time, F, is 10 μs; cross-connect configuration time, C, is 5 ms; message-processing time (including queueing delay) at a node, M, is 20 μs. We calculate T_{ij}^{sd} for sub-path as well as shared-path protection as follows. First, consider the period d_{is} right before link $< i, j >$ fails. Node s has been sending data, which will be lost when link $< i, j >$ fails. Second, upon detecting a link failure, node i sends a failure indication signal (FIS) to node s. This takes time $F + d_{is} + (h_{is} + 1) \times M$. Finally, upon receiving the FIS, node s sends a setup message to node d along the backup route, and waits for time $C + (h_b + 1) \times M$ before it switches to the backup route (configuring the cross-connects can be done in parallel). In summary, $T_{ij}^{sd} = F + 2 \times d_{is} + (h_{is} + 1) \times M + C + (h_b + 1) \times M$. The recovery time of link $< i, j >$, T_{ij}, is the recovery time averaged over all the connections that traverse $< i, j >$, i.e., $T_{ij} = (\sum_{(s,d) \in R} T_{ij}^{sd})/|R|$, where R is the set of connections whose working paths traverse $< i, j >$. The network-wide average recovery time, T, is defined as the summation of the probability that $< i, j >$ fails (p_{ij}) times the recovery time of link $< i, j >$, i.e., $T = \sum_{<i,j> \in Links} p_{ij} \times T_{ij}$. The worst-link recovery time is the maximum of T_{ij}^{sd} over all possible (s, d) and $< i, j >$ combinations.



(a) Comparison of recovery time. (b) Comparison of total number of wavelength-links.

Fig. 2. Results (The ILPs for shared-path protection failed for the last two cases after using up 2G RAM.)

Figure 2 (a) demonstrates that sub-path protection reduces the worst-link recovery time and the network-wide recovery time significantly, e.g., it reduces network-wide recovery time by 17.6% $(W = 6, D = 30)$~ 30.2% $(W = 6, D = 35)$, and worst-link recovery time by 29.8% $(W = 8, D = 40)$ ~ 43.2% $(W = 6, D = 25)$. Note that, under sub-path protection, the worst-link recovery time is below 50 ms in all cases. Thus, it is now possible to guarantee the 50 ms recovery time (as SONET ring does) in large mesh networks by properly partitioning the network and applying sub-path protection.

4.3 *Resource Utilization (Number of Wavelength-Links)*

Figure 2 (b) shows, as expected, that sub-path protection requires more resources, e.g., it sacrifices network resource utilization by 19.9% $(W = 8, D = 40)$ ~ 24% $(W = 6, D = 25)$. Our results also show that resource sacrifice decreases as the number of nodes or the number of connections increases because sub-path protection increases sharability between backup paths. Suppose there is a connection between node-pair $(4, 13)$. Its working path, p'_w, is $< 4, 7, 8, 9, 10, 13 >$ and backup path, p'_b, is $< 4, 3, 6, 5, 7, 11, 13 >$. Under shared-path protection, p'_b and p_b cannot share any wavelength because both p'_w and p_w traverse link $< 4, 7 >$. Under sub-path protection, however, p'_b and p_b can share the same wavelength on link $< 7, 11 >$ because each sub-path is independent from other sub-paths of the same path.

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