Subpath Protection for Scalability and Fast Recovery in Optical WDM Mesh Networks

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***Abstract*—This paper investigates survivable lightpath provisioning and fast protection switching for generic mesh-based optical networks employing wavelength-division multiplexing (WDM). We propose subpath protection, which is a generalization of shared-path protection. The main ideas of subpath protection are: 1) to partition a large optical network into smaller domains and 2) to apply shared-path protection to the optical network such that an intradomain lightpath does not use resources of other domains and the primary/backup paths of an interdomain lightpath exit a domain (and enter another domain) through a common domain-border node. We mathematically formulate the routing and wavelength-assignment (RWA) problem under subpath protection for a given set of lightpath requests, prove that the problem is NP-complete, and develop a heuristic to find efficient solutions. Comparisons between subpath protection and shared-path protection on a nationwide network with dozens of wavelengths per fiber show that, for a modest sacrifice in resource utilization, subpath protection achieves improved survivability, much higher scalability, and significantly reduced fault-recovery time.**

***Index Terms*—Fault management, lightpath, NP-completeness, optical network, partitioning, protection, wavelength-division multiplexing (WDM).**

I. Introduction

In a wavelength-routed optical network, the failure of a network element (e.g., fibers in a duct [1] and crossconnects [2]) can cause the failure of several lightpaths [3], thereby leading to large data and revenue loss. The development of fault and service management software, projected to grow significantly in the years ahead, is a top priority for service providers.

There are essentially two types of fault-management techniques: protection and restoration [4]–[6]. Throughout this paper, we refer to *protection* as a proactive procedure in which spare capacity is reserved during lightpath setup, and we refer to *restoration* as a reactive procedure in which the spare capacity available, if any, after a fault's occurrence is utilized for rerouting the disrupted lightpaths. A survivable lightpath has a *primary* path, which carries traffic during normal operation, and a *backup* path, which carries traffic when the primary path fails. Protection schemes can be classified by the type of rerouting as link-based versus path-based, by resource sharing as dedicated versus shared, or by failure dependency as failure independent versus failure dependent. In a link-based approach, lightpaths are rerouted around the end nodes of the failed link; in a path-based approach, a backup path is selected between the end nodes of the primary path. In dedicated protection, there is no sharing between backup resources, while in shared protection, backup paths can share wavelengths on some links as long as their corresponding primary paths are mutually diverse [7]. In a failure-dependent approach, the backup path of a lightpath correlates to failure scenarios, i.e., different failure scenarios may correspond to different backup paths, while in a failure-independent approach, a lightpath has one backup path, regardless of where a failure occurs. Shared-path protection is preferable because it utilizes network resources more efficiently than other protection schemes [6], [8], and failure-independent protection is desirable because it simplifies network management. Hereafter, we consider that a lightpath has fiber-disjoint primary and backup path pairs, i.e., we consider failure-independent shared-path protection.

A. Related Work

As networks migrate from stacked rings to meshes because of the poor scalability of interconnected rings and the excessive resource redundancy used in ring-based protection [9], mesh-structured protection schemes have been receiving increasing attention [4], [6], [8], [10]–[13]. We review the work on wavelength-division multiplexing (WDM) mesh protection for a given set of lightpath requests (which is the focus of this paper), and classify them based on whether they treat the underlying mesh as a whole, or they fragment the mesh into other protection domains [2], or they split an end-to-end lightpath into different segments.

The first category of work, as in [4], [6], [8], [10]–[12], proposes different protection schemes to protect the underlying mesh network as a whole. Specifically, the work in [6] develops integer linear programs (ILPs) for routing and wavelength assignment (RWA) with dedicated-path protection, shared-path protection, and shared-link protection against single-link

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failures. The objective is to minimize the total number of wavelength-links, where a wavelength-link is a wavelength on some link. The work in [4] considers two problems: determining the best backup route for each lightpath request, given the network topology, the capacities, and the primary routes of all requests; and determining primary and backup routes for each lightpath request to minimize network capacity and cost. ILP and distributed heuristic algorithms, under single-link or single-node failures, are presented. The work in [8] jointly optimizes primary and backup paths for path protection against single-link failures with failure-dependent protection. Lower bounds on spare-capacity requirements and integer-program formulations are presented. The work in [10] investigates the problem of routing, planning of primary capacity, rerouting, and planning of spare capacity in WDM networks. An ILP and a simulated-annealing-based heuristic are used to minimize the total cost for a given static traffic demand. The work in [12] formulates the RWA problem under dedicated-path and shared-path-protection constraints into integer programs, whose objective is to minimize the total facility cost, including both transmission and crossconnect cost. The work in [11] considers protection interoperability between optical layer (e.g., WDM transmission layer) and higher layer (e.g., IP layer). The authors design a network mapping between the two layers such that it respects the capacity constraints, survives from single-link or single-node failures, and ensures the number of lightpaths affected by such a failure is less than some given constant.

The second category of work, presented in [14]–[19], decomposes a mesh network into different structures, such as rings, protection cycles, digraphs, preconfigured cycles (p-cycles), or trees. Specifically, the work in [14] and [16] decomposes a mesh into 4-fiber rings (which [14] refers to as protection cycles), which then perform automatic protection switching (APS). The work in [18] creates primary and secondary digraphs based on a mesh so that the secondary digraph can be used to carry backup traffic that provides loop-back to the primary graph upon failures. The work in [17] proposes the use of preconfigured cycles, or p-cycles, where a cycle protects not only the lightpaths that are part of it, but also chords that run between cycle nodes. The work in [19] creates redundant trees on arbitrary node-redundant or link-redundant networks to combat against single-link or single-node failures. The work in [15] presents ILPs to decompose a WDM mesh network into self-healing rings.

The third category of work in [20]–[22] addresses mesh-structured protection against single-link failures by dividing a primary path into a sequence of segments and protecting each such segment separately. In particular, the approach in [20] divides a primary path into disjoint segments; the work in [21] and [22] divides primary paths into overlapped segments, thus the network survives from single-node failures.

By treating the underlying mesh network as a whole, the work in the first category can achieve optimal resource utilization since it has complete information on the entire network. It may, however, lead to long protection-switching time, and scalability can become a significant issue as the size of network increases. The work in the second category decomposes a mesh network into different types of protection structures and then applies APS or self-healing ring (SHR). While this may be a short-term solution for accommodating legacy ring algorithms and equipment, it may lead to excessive resource redundancy. As pointed out in [9], the minimum redundancy for a 1:1/DP (diverse protection) APS system is 100% and the redundancy of an SHR network is at least 100% and up to 300%. Because backup paths cannot be computed without knowledge of the segmentation points along the primary paths, the work in [20] and [22] computes primary paths prior to backup paths, which has been shown to be resource inefficient in [8] and [23]–[25]. While [21] dynamically divides a primary path into multiple segments, it does not accommodate backup sharing.

B. Multidomain Optical Networks and Our Proposal

Optical networks are expected to operate as multiple routing domains due to technological constraints, administrative functions, trust relationship, and other considerations [26]. An optical network domain is defined in [26] as "a portion of an interconnected optical network that has a clear demarcation boundary based on technology, business, service, technical administration, or architectural function." A group of products from the same vendor may consist of an optical network domain. Metro/core optical networks may comprise a multidomain optical network [27]. As optical networks evolve to multivendor heterogeneous networks, multiple optical network domains are likely to be needed [26], [28].

We propose a new protection scheme, called subpath protection, which combines the optical-domain idea with shared-path protection to achieve high scalability and fast recovery time for a modest sacrifice in resource utilization. *The main ideas of subpath protection are: 1) to partition a large optical network into several smaller domains and 2) to apply shared-path protection to the optical network such that an intradomain lightpath does not use resources of other domains and the primary/backup paths of an interdomain lightpath exit a domain (and enter another domain) through a common egress (or ingress) domain-border node (DBN).*

While subpath protection assumes the concept of shared-path protection underneath for routing within each domain, it can utilize other protection schemes such as dedicated-path protection as well. Subpath protection can even employ different protection schemes in different domains to provide differentiated quality of service (QoS) based protection for lightpath requests with differentiated availability requirements [29].

In this study, we assume that the optical network under investigation belongs to one single carrier since intercarrier-network communication is typically achieved via policy-based protocols such as border gateway protocol (BGP) on IP layer. We further concentrate on single-fiber[1] failures since they are the predominant form of failures in optical networks.[2]

[1]In this study, a fiber is considered to be bidirectional, and the term "link" refers to a unidirectional fiber.

[2]Other failure scenarios may include shared-risk-link-group (SRLG) failures [1], [7], and the more general shared-risk-group (SRG) failures. SRLG is an abstraction referring to a group of fibers that may be prone to a common failure. SRG is an abstraction referring to a group of network elements (including fibers, optical crossconnects, and other network components) that may be subject to a common failure.

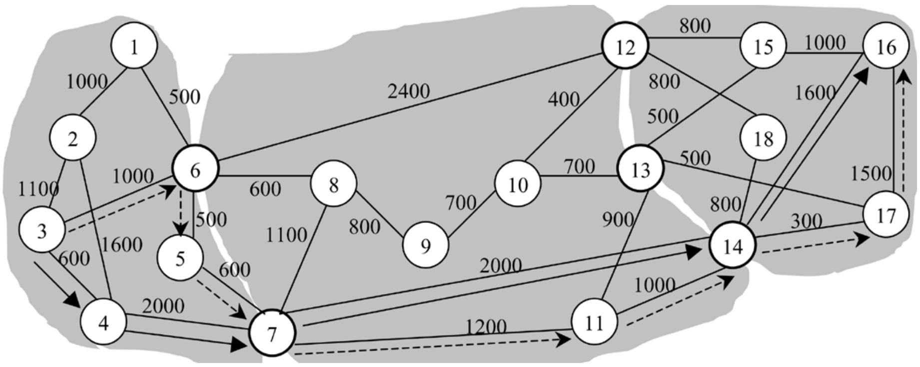


Fig. 1. An example nationwide network where each cloud denotes a domain. Domain 1 includes nodes 1–7 and the links in between (if there is a link between two DBNs of two domains, the link belongs to one domain only); domain 2 includes nodes 6–14 and the links in between; domain 3 includes nodes 12–18 and the links in between. Nodes 6, 7, 12, 13, and 14 are DBNs. The number besides each link is the length of the link in kilometers. The solid (dashed) arrows form the primary (backup) path between node pair (3, 16).

C. Organization

The rest of the paper is organized as follows. Section II discusses the different variants of subpath protection, proposes an approach to handle single-node failures, formally defines the problem of RWA under subpath protection, and proves that it is NP-complete. Section III mathematically formulates the RWA problem under subpath protection for a given set of lightpath requests. Section IV proves that the problem of finding optimal backup paths, under subpath-protection constraints (or shared-path-protection constraints) for a set of lightpath requests whose primary paths are given, is still NP-complete. This section also develops a heuristic to find efficient solutions. Section V compares the fault-recovery time, survivability, scalability, and resource utilization of subpath protection with those of shared-path protection. Section VI concludes this study.

II. Subpath Protection

A. Illustrative Example

Consider an interdomain lightpath between node-pair $(3, 16)$, as shown in Fig. 1. The primary path, p_p, is $\langle 3, 4, 7, 14, 16 \rangle$, and the backup path, p_b, is $\langle 3, 6, 5, 7, 11, 14, 17, 16 \rangle$. Note that p_p and p_b exit Domain 1 (and enter Domain 2) from the same DBN 7 and exit Domain 2 (and enter Domain 3) from the same DBN 14. DBNs 7 and 14 segment p_p and p_b into three subpaths, respectively, $\langle 3, 4, 7 \rangle (p_{p_1})$, $\langle 7, 14 \rangle (p_{p_2})$, and $\langle 14, 16 \rangle (p_{p_3})$ for p_p; $\langle 3, 6, 5, 7 \rangle (p_{b_1})$, $\langle 7, 11, 14 \rangle (p_{b_2})$, and $\langle 14, 17, 16 \rangle (p_{b_3})$ for p_b. Each (p_{p_i}, p_{b_i}) pair corresponds to the primary and backup paths of some intradomain segment of the lightpath. When link $\langle i, j \rangle$[3] (e.g., $\langle 7, 14 \rangle$) along p_p fails, instead of shutting down the entire primary path p_p and switching the traffic to p_b, our proposed scheme only turns down the subpath p_{p_k} (p_{p_2} in this example) that traverses the failed link, and switches the traffic to $p_{b_k}(p_{b_2})$. As a result, other subpaths (p_{p_1} and p_{p_3} in this example) that do not traverse link $\langle i, j \rangle$ are not affected.

B. Different Cases

Depending on the wavelength-conversion capability of DBNs, there are two cases of subpath protection. In the absence of wavelength converters at DBNs, the primary and backup paths of an interdomain lightpath must be on the same wavelength. Suppose DBNs 7 and 14 are wavelength continuous. If p_{p_1} is on wavelength w_1 and p_{b_2} is on w_2, when link $\langle 7, 11 \rangle$ fails, we cannot simply switch the traffic from p_{p_2} to p_{b_2} because p_{p_1} and p_{b_2} are on different wavelengths. If there are wavelength converters capable of full-range wavelength conversion at DBNs, then each subpath of one lightpath can be on any wavelength, regardless of the wavelength assignments of other subpaths of the same lightpath.

Depending on the administration of each domain, the implementation of DBNs may be different. Suppose that, in Fig. 1, Domain 1 and Domain 2 belong to different administrative entities. Then, in practice, DBN 6 (DBN 7 as well) is usually a logical node consisting of two nodes,[4] where each node belongs to one administrative entity and all the physical nodes are interconnected through high-capacity links. If both Domain 1 and Domain 2 belong to the same administrative entity, then in practice DBN 6 (DBN 7 as well) may be implemented using one node but it can be implemented using multiple nodes too. We assume that the links between the nodes of a DBN are $1 + 1$ protected [27], as is usually done in practice, and treat all such nodes as one logical node in this study.

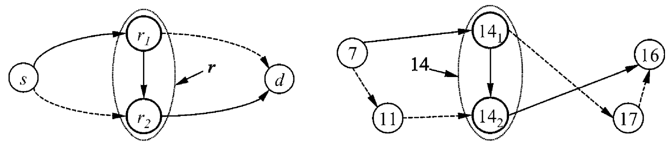
C. Domain-Border-Node (DBN) Failures

It may appear that subpath protection may be susceptible to single-node failures at a DBN since the primary and backup paths of an interdomain lightpath traverse common DBNs. In the following, we show one possible approach to dealing with single-node failures.

Consider an interdomain lightpath between node pair (s, d). Suppose that the lightpath traverses DBN r. We can construct the DBN r by using two physical nodes r_1 and r_2 interconnected by a fiber, as shown in Fig. 2(a). (Fig. 2(b) shows DBN 14 in Fig. 1 so constructed.) Next, we show that the lightpath survives from any single fiber/node failures and still enjoys the benefits of subpath protection, assuming that the two subpaths between node s and DBN r (DBN r and node d) are fiber/node disjoint.

[3]Throughout this paper, we use $\langle i, j \rangle$ and ij interchangeably to denote link $i \rightarrow j$: We use $\langle i, j \rangle$ in the text and ij in the formulations in later sections.

[4]Each of these nodes can again be a logical node consisting of multiple physical nodes for fault-tolerant purpose, as will be shown in Section II-C .



(a) Implementation of DBN r (b) Implementation of DBN 14 in Fig. 1

Fig. 2. A possible DBN implementation to combat single-node failures. Primary (backup) paths are in solid (dashed) arrows.

By the construction of DBN r, if link $\langle r_1, r_2\rangle$ fails, the lightpath can take either path $\langle s, r_1, d\rangle$ or path $\langle s, r_2, d\rangle$ to carry traffic. Thus, the interdomain lightpath survives from single-fiber failures.

By the construction of DBN r, if physical node r_1 fails, the lightpath can take path $\langle s, r_2, d\rangle$ to carry traffic; if physical node r_2 fails, the lightpath can take path $\langle s, r_1, d\rangle$ to carry traffic. Thus, the interdomain lightpath survives from single-node failures.

Meanwhile, this construction allows an interdomain lightpath to enjoy the benefits of subpath protection, i.e., any single fiber/node failure only affects a segment of the entire lightpath. For example, if any fiber/node between node s and node r_1 fails, node s can switch the traffic to the path $\langle s, r_2\rangle$; if node r_1 fails, node s can switch to the subpath $\langle s, r_2\rangle$; if node r_2 fails, node r_1 can switch to the subpath $\langle r_1, d\rangle$; if any fiber/node between node r_2 and node d fails, r_1 can switch the traffic to the subpath $\langle r_1, d\rangle$. In general, any single fiber/node failure only affects one domain.

While we may consider that nodes r_1 and r_2 employ $1+1$ redundancy, we can deliberately group two nodes as a logical DBN to avoid redundancy; and subpath protection can still function properly. For example, we can group nodes 6 and 7 as a logical DBN, and nodes 12 and 14 as another logical DBN in Fig. 1. In that case, the lightpath request between node pair (3, 16) can have $\langle 3, 6, 5, 7, 14, 18, 12, 15, 16\rangle$ as primary path. Its backup subpaths can be $\langle 3, 4, 7\rangle$, $\langle 6, 12\rangle$, and $\langle 14, 17, 16\rangle$. (There are details such as coordination between nodes in a logical DBN, but we are skipping them to conserve space.)

Other possible ways of dual-node-interconnection approaches, such as Drop and Continue for SONET ring interconnection, can be found in [30] and [31].

D. Problem Statement

We first define the notations and then formally state the RWA problem with subpath protection. A network is represented as a weighted, directed graph $G = (V, E, C)$, where V is the set of network nodes, E is the set of unidirectional links, and $C : E \rightarrow Z^+$ is the cost function for each link (Z^+ denotes the set of positive integers). A *domain* A on G is the node-induced subgraph $G_A = (V_A, E_A, C_A)$, where $V_A \subseteq V$, E_A contains all the links of E, both end points of which are in E_A, and $C_A : E_A \rightarrow Z^+$ is C restricting to E_A. A *partitioning configuration* $\mathcal{P}$ is a set of domains. A *domain-border node (DBN)* of $\mathcal{P}$ is a node that belongs to multiple domains of $\mathcal{P}$. The set of DBNs $\mathcal{R}$ for a partitioning configuration $\mathcal{P}$ is defined as $\mathcal{R} = \cup_{A, A' \in \mathcal{P}}(V_A \cap V_{A'})$. A partitioning configuration $\mathcal{P}$ is *proper* if each DBN of $\mathcal{P}$ has an in-degree of at least two in each domain it belongs to, and there is no link that crosses multiple domains. A lightpath-request set $\mathcal{D}$, $\mathcal{D} \subset V \times V$, is a set of source-destination pairs, where each pair represents a lightpath request from the source node to the destination node.[5]

The RWA for the primary and backup paths of $\mathcal{D}$ satisfies the *shared-path-protection constraints* as follows.

- C.1) The primary and backup paths of a lightpath are fiber-disjoint.
- C.2) Two primary paths do not utilize the same wavelength on any common link they traverse.
- C.3) A primary path does not share any wavelength with any backup path on any common link they traverse.
- C.4) Two backup paths can share a wavelength on a common link only if their corresponding primary paths are fiber disjoint.

The RWA for the primary and backup paths of $\mathcal{D}$ satisfies the *domain constraints* as follows.

- C.5) The primary and backup paths of an intradomain lightpath k ($\exists A \in \mathcal{P}$ s.t. $k_s, k_d \in A$, where k_s and k_d are the source and destination nodes of lightpath k) only use the resources of its own domain (domain A).
- C.6) The primary and backup paths of an interdomain lightpath k ($\forall\, A \in \mathcal{P}, \wedge\neg(k_s, k_d \in A)$) exit a domain (and enter another domain) through a common DBN.

The RWA for the primary and backup paths of $\mathcal{D}$ satisfies the *subpath-protection constraints* if it satisfies both shared-path-protection constraints and domain constraints.

We now formally state the RWA problem in an optical WDM mesh network with subpath protection as follows. Given a network G with W wavelengths per link, a partitioning configuration $\mathcal{P}$, and a set of lightpath requests $\mathcal{D}$, route each lightpath on G and assign a wavelength to each path under subpath-protection constraints such that the total network cost is minimized (which effectively maximizes the network throughput when network resources, e.g., number of wavelengths per link, are limited).

In this study, we assume the partitioning configuration of a network is given and it is proper. How to partition a large optical network into smaller domains involves administrative issues and is not addressed here. A related approach on partitioning a network can be found in [32]. We also assume that DBNs are wavelength convertible since, in practice, optical domains are expected to be isolated by transponders [26], making wavelength conversion available at DBNs.

E. Proof of NP-Completeness

While the static lightpath establishment (SLE) problem has been shown to be NP-complete for wavelength-continuous network with $W \geq 3$ wavelengths [3], so far there is no concrete proof in the literature that RWA under shared-path protection is NP-complete. We prove that RWA under shared-path protection is NP-complete, even for $W = 1$. That RWA under subpath protection is NP-complete follows since the former is a special case of the latter when the number of domains is one. We formally state the decision version of the RWA under shared-path protection (RWASPP) as follows.

[5]If there are multiple lightpath requests between the same source-destination pair, then $\mathcal{D}$ contains multiple copies of that source-destination pair.

Instance: A graph G with W wavelengths per link, and a set of lightpath requests $\mathcal{D}$.

Question: Does there exist a set of $|\mathcal{D}|$ link-disjoint path-pairs, one for each lightpath request, satisfying shared-path-protection constraints?

Theorem 1: RWASPP is NP-complete.

Proof: Please see Appendix I. ∎

A direct application of Theorem 1 is that RWA under shared or subpath protection is NP-complete for wavelength-convertible networks since the proof holds when the number of wavelengths is unity.

III. ILP Formulation for RWA With Subpath Protection

We formulate the RWA problem under subpath protection for a given set of lightpath requests under a nonblocking model, i.e., all lightpath requests can be successfully routed. The formulation turns out to be an integer linear program. As combined RWA ILP [33] is too time-and-space intensive due to the NP-completeness of the problem, we develop a two-step ILP for routing and for wavelength assignment separately. There are two main reasons for developing a two-step ILP for separated routing and wavelength assignment. First, pure routing without wavelength assignment becomes much more computationally efficient because the stringent wavelength-continuity constraint is gone. Meanwhile, we can still take into consideration backup sharing in the pure routing step, as we will show later in the formulation. Second, after routing has been done, wavelength assignment can be performed on a per-domain basis due to the wavelength-conversion capability of DBNs. The complexity of wavelength assignment is significantly reduced because each domain has a lot fewer lightpath requests to consider: Each domain only needs to worry about its intradomain lightpath requests and a portion of the interdomain lightpath requests which traverse this domain (compared to the entire set of lightpath requests in the no-domain case). We remark that both the routing problem and the wavelength-assignment problem are still NP-complete.

We first find, for each lightpath request, two fiber-disjoint paths with respect to subpath-protection constraints while maximizing the potential sharing between backup paths; then, we convert each interdomain lightpath to a collection of intradomain lightpaths by partitioning its interdomain fiber-disjoint paths at the common DBNs they traverse; finally, we assign wavelengths to all the subpaths within one domain, and repeat the wavelength-assignment process for each domain.

Below we first define the notations; then, we present the split (two-step) ILP formulation; finally, we demonstrate the equivalence of the ILP to the original problem. We assume that DBNs are wavelength convertible while other nodes are wavelength continuous in these example formulations shown below, but they can be generalized.

A. Notations

The following are given as inputs.

- N — Number of nodes in the network;
- W — Number of wavelengths available on each link. We use w to index each wavelength, i.e., $1 \leq w \leq W$. For the formulations reported here, we assume that the same number of wavelengths are available on all links, but this too can be generalized;
- $E = \{ij\}$ — Set of unidirectional links in the network. We use ij to denote the link between node i and node j, and (i, j) to denote node pair i and j.
- $\mathcal{D}$ — Set of lightpath requests, $|\mathcal{D}| = D$. We use k to denote the kth lightpath request, and we use k_s and k_d to denote the source and the destination nodes of this lightpath request.
- $\mathcal{P}$ — Partitioning configuration.
- $\mathcal{R}$ — Set of domain-border nodes.
- C_{ij} — Cost associated with link ij.

B. Subpath Protection: Split ILP Formulation

1) Part I: Routing: Part I computes the primary and backup paths for each lightpath request subject to fiber-disjoint-path-pair constraint C.1 and domain constraints C.5–C.6 (in Section II-D), taking into consideration the maximal wavelength-link sharing potential between backup paths.

Part I solves for the following variables:

- F_{ij}^{k} — takes on the value 1 if the primary path for lightpath k utilizes link ij, 0 otherwise;
- S_{pq}^{k} — takes on the value 1 if the backup path for lightpath k utilizes link pq, 0 otherwise;
- $\delta_{pq}^{k,ij}$ — takes on the value 1 if lightpath k utilizes link ij along its primary path and link pq along its backup path;
- W_{ij} — total number of wavelengths required on link ij.

Objective: The objective function (1) minimizes the total number of resources required. If C_{ij} is 1 for all the links, then the objective is to minimize the total number of wavelength-links (as in [6]); if C_{ij} is the mileage of link ij, then the objective is to minimize the total wavelength miles (as in [15]), which effectively minimizes the average network delay since the link propagation delay dominates the processing delay at intermediate nodes as long as link utilization is not too close to unity [34]. C_{ij} can use complex cost functions as in [10], [12] as long as it is linear. For the numerical results reported later, we let C_{ij} be 1 to minimize total number of wavelength-links. In general, the objective function is

$$\text{Minimize} \quad \sum_{ij \in E} (W_{ij} \times C_{ij}). \tag{1}$$

Constraints: The first set of constraints (2) is the multicommodity-flow equations that account for the routing of the primary path for each lightpath request

$$\sum_{j} F_{ij}^{k} - \sum_{j} F_{ji}^{k} = \begin{cases} 1, & \text{if } i = k_s \\ -1, & \text{if } i = k_d \\ 0, & \text{otherwise} \end{cases} \qquad \forall\, 1 \leq k \leq D,\ 1 \leq i \leq N. \tag{2}$$

Similarly, the set of constraints in (3) is the multicommodity-flow equations that account for the routing of the backup path for a lightpath when a link fails. We remark that $\delta_{pq}^{k,ij}$ and S_{ij}^{k} are closely related and (3) can be implemented by using S_{ij}^k too. The reason we introduce $\delta_{pq}^{k,ij}$ is to maximize backup sharing. These constraints are

$$\sum_q \delta_{pq}^{k,ij} - \sum_q \delta_{qp}^{k,ij} = \begin{cases} F_{ij}^k, & \text{if } p = k_s \\ -F_{ij}^k, & \text{if } p = k_d \\ 0, & \text{otherwise} \end{cases}$$
$$\forall\, 1 \le k \le D,\ ij \in E,\ 1 \le p \le N. \quad (3)$$

The set of constraints in (4) and (5) derives S_{pq}^k from $\delta_{pq}^{k,ij}$

$$S_{pq}^k \le \sum_{ij \in E \wedge i, j \in A} \delta_{pq}^{k,ij} |E| \times S_{pq}^k \ge \sum_{ij \in E \wedge i, j \in A} \delta_{pq}^{k,ij}$$
$$\forall\, k,\ A \in \mathcal{P},\ pq \in E \wedge p,\ q \in A. \quad (4)$$

The set of constraints in (5) ensures that the primary and backup paths of one lightpath are fiber-disjoint

$$\delta_{ij}^{k,ij} = 0, \quad \delta_{ij}^{k,ji} = 0 \quad \forall\, k, \forall\, ij, ji \in E. \quad (5)$$

The set of constraints in (6) and (7) states the capacity requirements on each link. Please note that backup sharing is implicitly captured in (6). The limit on the number of wavelengths per fiber is enforced by (7)

$$\sum_k (F_{ij}^k + \delta_{ij}^{k,pq}) \le W_{ij} \quad (6)$$
$$\forall\, A \in \mathcal{P},\ ij \in E \wedge i,\ j \in A,$$
$$pq \in E \wedge p,\ q \in A$$
$$W_{ij} \le W \quad \forall\, ij \in E. \quad (7)$$

The set of constraints in (8) and (9) is domain related, and when combined with (6) they ensure that domains are autonomous. Equation (8) applies to intradomain lightpath requests, i.e., intradomain lightpath requests should not use resources of other domains.[6] If the predicate $(\forall\, k \wedge (\exists A \in \mathcal{P}\text{s.t. } k_s, k_d \in A))$ is true, then the source node k_s and the destination node k_d belong to the same domain A. (We remark that k_s and k_d may be DBNs and, thus, they can belong to multiple domains. If this is the case, we randomly pick one domain that they belong to.) Equation (9) applies to interdomain lightpaths, and it ensures that primary and backup paths of an interdomain lightpath exit a domain (and enter another domain) through a common DBN. The predicate $(\forall\, A' \in \mathcal{P}, \forall\, k \wedge \neg(k_s, k_d \in A'))$ is true if and only if the source node k_s and the destination node k_d belong to different domains. This case may be tricky, as shown in Fig. 1. The backup subpath $\langle 3,6,5,7 \rangle$ traverses DBN 6 first and then exits Domain 1 via a different DBN 7. By considering the net flow of outgoing lightpath requests to other domains at DBNs, (9) ensures that the primary subpath $\langle 3,4,7 \rangle$ exits Domain 1 via DBN 7 instead of DBN 6. These constraints are

$$F_{ij}^k = 0 \quad S_{ij}^k = 0$$
$$\forall\, k \wedge (\exists A \in \mathcal{P}\text{s.t.} k_s, k_d \in A),$$
$$\forall\, i \notin A \vee j \notin A \quad (8)$$

[6]In our implementation of the ILP for the topology shown in Fig. 1, we completely got rid of these zero variables stated in (8) and sped up the solution process. While it may be possible to eliminate most of these zero variables for a particular instance of the problem, note that some of them may be nonzero, and our objective is to also provide a compact mathematical formulation of the problem (which can be customized as needed for specific implementations, as we have done).

$$\sum_{\forall\, i \in A: ij \in E} F_{ij}^k - \sum_{\forall\, e \in A: je \in E} F_{je}^k$$
$$= \sum_{\forall\, i \in A: ij \in E} S_{ij}^k - \sum_{\forall\, e \in A: je \in E} S_{je}^k$$
$$(\forall\, A' \in \mathcal{P}, \forall\, k \wedge \neg(k_s, k_d \in A')),\ \forall\, A \in \mathcal{P},$$
$$\forall\, j \in \mathcal{R} \wedge j \in A. \quad (9)$$

The final set of constraints states that F_{ij}^k, S_{pq}^k, and $\delta_{pq}^{k,ij}$ are binaries while W_{ij} is integer [W_{ij} is bounded by W in (7)]

$$F_{ij}^k, S_{pq}^k, \delta_{pq}^{k,ij} \in \{0,1\}, \quad W_{ij} \in \text{integer}$$
$$\forall\, 1 \le k \le D,\ ij, pq \in E. \quad (10)$$

We remark that Part I can accommodate other objective functions such as minimizing the total number of wavelengths. To minimize the total number of wavelengths, we can use Minimize W as the objective function (W becomes a variable in that case). The flow-conservation constraints (2) and (3) may not be efficient in avoiding loops in the paths. We can add additional constraints as proposed in [35] to address this problem. The basic idea is to make sure that a path only traverses fibers that are part of a subset of the physical topology called a covering tree. To model the routing problem under shared-path protection, we simply make the number of domains $|\mathcal{P}|$ be unity and the DBN set $\mathcal{R}$ be empty.

Based on the routing results, we segment the fiber-disjoint path pair of an interdomain lightpath request according to the common DBNs the path pair traverses; we then collect all the fiber-disjoint path pairs of a domain and use the following Part II to assign wavelength to every path on a per-domain basis.

One critical assumption here, and later for the heuristic, is that all the DBNs are wavelength convertible. Without this assumption, wavelength assignment for multiple domains is coupled by the wavelength-continuity constraint and per-domain independent wavelength assignment may not be possible. In practice, optical domains are expected to be isolated by transponders [26], making wavelength conversion available at DBNs and making this assumption realistic.

2) Part II: Wavelength Assignment: Part II assigns wavelengths to the primary and backup paths of all the lightpaths within one domain subject to shared-path-protection constraints C.2–C.4 (in Section II-D) and wavelength-continuity constraints. The following are given as inputs:

- p_p^k primary path for lightpath k. We use $ij \in p_p^k$ to denote that p_p^k traverses link ij;
- p_b^k backup path for lightpath k;
- w_{ij} number of wavelengths used by primary paths on link ij. (We can derive w_{ij} from p_p^k, i.e., $w_{ij} = \sum_{k: ij \in p_p^k} 1$, since primary paths are fixed.)

Part II solves for the following variables:

- F_w^k takes on the value 1 if the primary path for lightpath k utilizes wavelength w;
- S_w^k takes on the value 1 if the backup path for lightpath k utilizes wavelength w;
- m_{ij}^w takes on the value 1 if wavelength w on link ij is used by some backup path;
- s_{ij} denotes the number of wavelengths used by backup paths on link ij.

Objective: The objective function (11) minimizes the total amount of resources used by backup paths since the amount of resources used by primary paths is the fixed value, $\sum_{ij\in E}(w_{ij}\times C_{ij})$

$$\text{Minimize} \sum_{ij}(s_{ij}\times C_{ij}). \tag{11}$$

The set of constraints in (12) and (13) ensures that each lightpath is assigned a wavelength

$$\sum_{w=1}^{W} F_w^k = 1 \quad \forall\, k \tag{12}$$

$$\sum_{w=1}^{W} S_w^k = 1 \quad \forall\, k. \tag{13}$$

The set of constraints in (14) and (15) decides whether a wavelength on a link is used by some backup path

$$m_{ij}^w \le \sum_{k:ij\in p_b^k} S_w^k \quad \forall\, ij\in E \tag{14}$$

$$D\times m_{ij}^w \ge \sum_{k:ij\in p_b^k} S_w^k \quad \forall\, ij\in E. \tag{15}$$

The set of constraints in (16) states that the primary and backup paths cannot share any wavelength-link

$$m_{ij}^w + \sum_{k:ij\in p_p^k} F_w^k \le 1 \quad \forall\, ij\in E, w. \tag{16}$$

The set of constraints in (17) ensures that two backup paths can not share any wavelength-link if their corresponding primary paths are not fiber-disjoint

$$\sum_{k:ij\in p_p^k\wedge pq\in p_b^k} S_w^k \le 1 \quad \forall\, w,\ \forall\, ij,pq\in E. \tag{17}$$

The set of constraints in (18) decides the number of wavelengths used by backup paths on link ij

$$s_{ij} = \sum_{w=1}^{W} m_{ij}^w \quad \forall\, ij\in E. \tag{18}$$

The set of constraints in (19) ensures that the number of wavelengths used on each link is no more than the total number of wavelengths available

$$w_{ij} + s_{ij} \le W \quad \forall\, ij\in E. \tag{19}$$

The final set of constraints in (20) states that F_w^k, S_w^k, m_{ij}^w are binaries and s_{ij} is integer [s_{ij} is bounded by W in (19)]

$$F_w^k, S_w^k, m_{ij}^w \in \{0,1\}, \quad s_{ij}\in \text{integer} \\ \forall\, 1\le k\le D,\ 1\le w\le W,\ ij\in E. \tag{20}$$

Note that we can also use Minimize W as the objective to minimize the number of wavelengths.

C. Equivalence of the Split ILP and the Original Problem

We demonstrate the equivalence of the split ILP and the RWA problem with subpath protection by showing that any valid solution produced by the ILP satisfies the original Constraints C.1–C.6 and vice versa. First, the primary and backup paths for a lightpath request are formed by the flow-conservation constraints in (2) and (3). Constraint C.1 is ensured in (5). Constraints C.2 and C.3 are formulated in (12), (13), and (16). Constraint C.4 is enforced by (17). Constraint C.5 is ensured in (8). Constraint C.6 is captured in (9). The constraint on the number of wavelengths per fiber is accommodated by (6), (7), and (19). The objective of the problem to minimize total network cost is formulated in the two objective functions (1) and (11). The other equations, such as (4) and (5), are used to derive intermediate variables. Later, in Section V, we shall present illustrative results from the split ILP.

IV. Heuristic

While ILPs are useful in providing insights into the nature of the problem, they may be hard to solve for large networks with dozens of wavelengths per link because of the long computational time caused by the NP-completeness of the original problem (please refer to Section III). We propose a heuristic for RWA under subpath-protection constraints for a given set of lightpath requests and evaluate its effectiveness. The crucial observation from the split ILP is that, once fiber-disjoint paths are found for each interdomain lightpath request, wavelength assignment is of local (a domain) matter. This inspires us to investigate algorithms to segment interdomain lightpaths, and then to assign wavelengths on a per-domain basis.

The heuristic has three phases. Phase 1 computes the shortest fiber-disjoint path pair for each lightpath request subject to domain constraints and then partitions each interdomain lightpath into a set of subpaths according to the common DBNs the lightpath's primary and backup paths traverse. The solution found in this phase serves as the seed solution for later optimization. Phases 2 and 3 work on a per-domain basis. Phase 2 assigns wavelengths to all the paths of a domain. Phase 3 first reroutes—for all the fiber-disjoint path pairs of a domain—the backup paths to increase backup sharing with respect to shared-path-protection constraints, and then it rearranges the primary paths to reduce the number of wavelength-links a primary path uses.

The heuristic takes as input a network as a weighted, directed graph G; the number of wavelength, W, on each fiber; a proper partitioning configuration $\mathcal{P}$; and a given set of lightpath requests $\mathcal{D}$. The heuristic outputs the routing and wavelength assignment of the primary and backup paths for each lightpath request.

A. Phase 1: Find Shortest Path Pair for Each Lightpath With Respect to Domain Constraints

Phase 1 computes the shortest fiber-disjoint paths for each lightpath request subject to domain constraints, i.e., the primary and backup paths of an interdomain lightpath exit a domain (and enter another domain) through a common DBN and an intradomain lightpath cannot use resources of other domains. As the routing problem under shared-path (or subpath) protection constraints with multiple lightpath requests is NP-complete, Phase 1 works on a per-lightpath basis (backup sharing will be considered later).

For any lightpath request $k \in \mathcal{D}$, if k is an intradomain lightpath request, the heuristic directly applies a known shortest link-disjoint path-pair algorithm (e.g., Suurballe's algorithm [36] or the algorithm in [23]); if k is an interdomain lightpath request, the heuristic constructs a weighted, directed auxiliary graph G_a^k such that, when transformed back to G, the shortest path between (k_s, k_d) in G_a^k is the shortest fiber-disjoint path pair for (k_s, k_d) in G. G_a^k has k_s, k_d, and all the DBNs as its vertices. The cost of a link in G_a^k is the cost of the shortest fiber-disjoint path pair between the end-nodes of that link in G. Phase 1 works as follows.

Step 1) Construct a weighted, directed graph $G_a = (V_a, E_a)$ where:
- $V_a = \mathcal{R}$, the set of DBNs;
- $\forall\, i \neq j \in V_a$, $ij \in E_a$ if and only if $\exists A \in \mathcal{P}$ s.t. $i, j \in A$;
- C_{ij}, the cost of link ij, is the cost of the shortest fiber-disjoint path pair between node pair (i, j) among all such path pairs in any domain A such that $i \in A \wedge j \in A$ in G.

Then, the heuristic applies the following steps to each interdomain lightpath k (k is an interdomain lightpath if and only if $\forall\, A \in \mathcal{P}, \neg(k_s, k_d \in A)$).

Step 2) Construct a weighted, directed graph $G_a^k = (V_a^k, E_a^k)$ as follows (assume $k_s \in A_s$, $k_d \in A_d$, $A_s \neq A_d \in \mathcal{P}$).
- $V_a^k = V_a \cup \{k_s, k_d\}$.
- E_a^k comprises the following three components:
  a) $\forall\, r \in \mathcal{R} \wedge r \in A_s$, $k_s r \in E_a^k$, C_{sr} is the cost of the shortest fiber-disjoint path pair between (k_s, r) in A_s;
  b) $\forall\, r \in \mathcal{R} \wedge r \in A_d$, $r k_d \in E_a^k$, C_{rd} is the cost of the shortest fiber-disjoint path pair between (r, k_d) in A_d;
  c) $\forall\, r_1 \neq r_2 \in \mathcal{R} \wedge \neg(r_1, r_2 \in A_s \vee r_1, r_2 \in A_d)$, $r_1 r_2 \in E_a^k$, and it has the same cost as $r_1 r_2$ in G_a.

Step 3) Compute the shortest path between (k_s, k_d) in G_a^k. Let it be $\langle r_0 = k_s, r_1, \ldots, r_k, r_{k+1} = k_d \rangle$.

Step 4) Concatenate the shortest fiber-disjoint path pair between r_i and r_{i+1} in G, for $i = 0, 1, \ldots, k$, to obtain the shortest fiber-disjoint path pair for lightpath k in G.

Fig. 3 shows G_a and $G_a^{3,16}$ for the graph in Fig. 1. Conceptually, we only need G_a^k. The reason we have G_a is to avoid unnecessary repetitive computation in Step 2.2.c.

B. Phase 2: Wavelength Assignment

Wavelength-assignment heuristics have been extensively studied [37]. We use the wavelength-assignment algorithm in

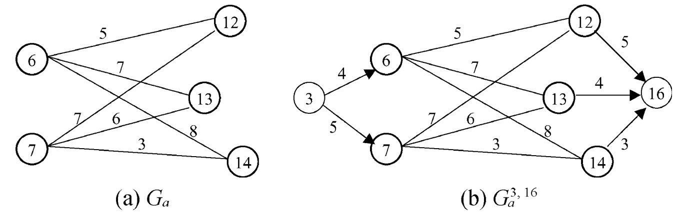


Fig. 3. Auxiliary graphs for the network shown in Fig. 1. The number on a link is the cost of that link, assuming the cost of each link in Fig. 1 is unity. A link with arrow is a unidirectional link; a link without an arrow is a bidirectional link.

[38] for the sake of simplicity because our main interest is a heuristic that finds efficient solutions. The basic ideas are to transform the wavelength assignment of primary and backup paths to the graph-coloring problem, and to employ a sequential coloring [39], [40] algorithm. Phase 2 works on a per-domain basis since an interdomain lightpath is segmented into a set of subpaths in Phase 1. The shorter path of the fiber-disjoint path pair is considered as the primary path, and the longer one is the backup path. Phase 2 works as follows.

First, we construct an undirected graph, G_c, in which each path is treated as a vertex. The edges are constructed as follows: two primary paths are adjacent in G_c if they traverse a common fiber; a primary path and a backup path are adjacent if they traverse a common fiber; two backup paths are adjacent if their corresponding primary paths traverse a common fiber. We then sequentially color all the vertices such that adjacent vertices have different colors. The sequential order is smallest-last [40] in which the vertex of smallest degree is colored last.

C. Phase 3: Optimization

The sole purpose of this optimization procedure is to rearrange the primary and backup paths to reduce the total number of wavelength links used. A similar approach can be found in [4]. In step one of this two-step procedure, we reroute the backup paths to increase backup sharing. In step two, we rearrange the primary paths since there may be a shorter path available after rerouting the backup paths. Please note that Phase 3 also works on a per-domain basis.

Before describing the optimization procedure, we prove that the problem of routing the backup paths to find the optimal solution is NP-complete. We formally state the optimal-backup-routing (OBR) problem as follows.

OBR: Given a WDM network with W wavelengths on each link as a weighted, directed graph $G = (V, E, C)$, an integer c, and a set $\mathcal{D}$ of lightpath requests whose primary paths, $p_p^k (1 \leq k \leq |\mathcal{D}|)$, are known, does there exist a backup path for each lightpath request subject to shared-path-protection constraints (C.1–C.4 in Section II-D) such that the total cost of the backup paths is no more than c?

Theorem 2: The OBR problem is NP-complete.

Proof: Please see Appendix II. ■

Step one starts with randomly picking one lightpath, say k, with primary path p_p^k and backup path p_b^k. Next, remove the backup path p_b^k and update the cost of wavelength w on link ij, C_{ij}^w, as follows ($+\infty$ is a large number, e.g., the diameter of the network times the maximum link cost, where the diameter of the network is defined as the total number of hops of the longest path in the network):

$$C_{ij}^{w} = \begin{cases} +\infty, & \text{if } p_p^k \text{ traverses link } ij\text{, or wavelength } w \text{ on link } ij \text{ is used by some primary paths, or wavelength } w \text{ on link } ij \text{ is used by some backup path whose primary path is not mutually diverse with } p_p^k \\ C_{ij}, & \text{if wavelength } w \text{ on link } ij \text{ is not used} \\ 0, & \text{otherwise.} \end{cases}$$

Then, compute the minimal-cost path from k_s to k_d on each wavelength layer, and pick the one with the minimal cost as the backup path. Note that the fiber-disjoint constraints and the constraint that two backup paths cannot share resources if their primary paths are not fiber-disjoint are ensured by the cost function, and the newly computed backup has a cost no larger than p_b^k.

Lastly, repeat this process for a predefined number of times or until it converges, i.e., the new backup path does not have smaller cost compared to the previous one for a predefined number of times.

Instead of simply admitting the newly computed lightpath with minimum cost, we tried a simulated-annealing based approach. In this approach, we admit the new minimum-cost lightpath only when the cost difference $\triangle$ between the old backup path and the new one is greater than a threshold, which decreases gradually; or $e^{-\triangle}$ is less than a random number between 0 and 1. We found that simply admitting the newly computed lightpath works better in terms of resource utilization when the number of iterations is modest. The reason is that the simulated-annealing-based approach needs more time to converge.

Step two is similar to Step one, except that we remove the primary path p_p^k and update the cost of wavelength w on link ij according to the following cost function:

$$C_{ij}^{w} = \begin{cases} +\infty, & \text{if } p_b^k \text{ traverses link } ij\text{, or } p_b^k \text{ shares some wavelength-link with some backup path whose primary path traverse link } ij\text{, or wavelength } w \text{ on link } ij \text{ is used by some lightpath} \\ C_{ij}, & \text{otherwise.} \end{cases}$$

We prove the correctness of our heuristic in Appendix III.

D. Complexity

The complexity of Phase 1 is $O(N^4 + D \cdot N^3)$ (assuming Dijkstra's algorithm for shortest-path computation). The complexity of Step 1.1–Step 1.3 is $O(N^4)$ since $V_a = |\mathcal{R}| \leq N$, $E_a < |V_a|^2 <= N^2$, and each link of G_a takes time $O(N^2)$ to compute. The complexity of Step 2.1 is $O(N)$, and Step 2.2 is $O(N^3)$ (Step 2.2.1: $O(N^3)$, Step 2.2.2: $O(N^3)$, and Step 2.2.3: $O(N^2)$). Thus, the complexity of Step 2 is $O(D \cdot N^3)$. The complexities of Step 3 and Step 4 are $O(N^2)$ and $O(A)$, respectively.

The complexity of Phase 2 is $O(N \cdot D^2)$. The complexity of constructing G_c is $O(N \cdot D^2)$ because we need to compare $2 \cdot D$ paths, each of which is of length less than N. The complexity of sequential coloring is $O(D \cdot W)$, where W is the maximum number of colors and W is no more than $2 \cdot D$.

The complexity of Phase 3 is $O(K \cdot W \cdot N^3 \cdot D)$, where K is the number of times Step 1 (in Phase 3) repeats. The complexity of calculating the cost function for each wavelength-link on one wavelength layer is $O(N \cdot D)$. The complexity of the shortest-path algorithm is $O(N^2)$. The complexity of computing the shortest path on one wavelength layer (including calculating the cost function) is $O(N^3 \cdot D)$ since each wavelength layer can have $O(N^2)$ links. Since we have W wavelength layers and we need to repeat the entire process K times, the complexity of Phase 3 is $O(K \cdot W \cdot N^3 \cdot D)$.

The total complexity of the heuristic is thus $O(N^4 + D \cdot N^3 + |\mathcal{P}|(N \cdot D^2 + \cdot K \cdot W \cdot N^3 \cdot D) = O(|\mathcal{P}| \cdot K \cdot N^3 \cdot D^2)$ since, in general, D is larger than N and W. We remark that this is a loose worst case upper bound, and the complexity is much less in practice since a domain only has $\lceil N/|\mathcal{P}| \rceil$ nodes on average (while the complexity analysis considers that a domain has N nodes). Furthermore, Phase 1 can be carried out in parallel for each lightpath request, and Phase 3 can be carried out in parallel on each wavelength layer.

V. Results and Discussions

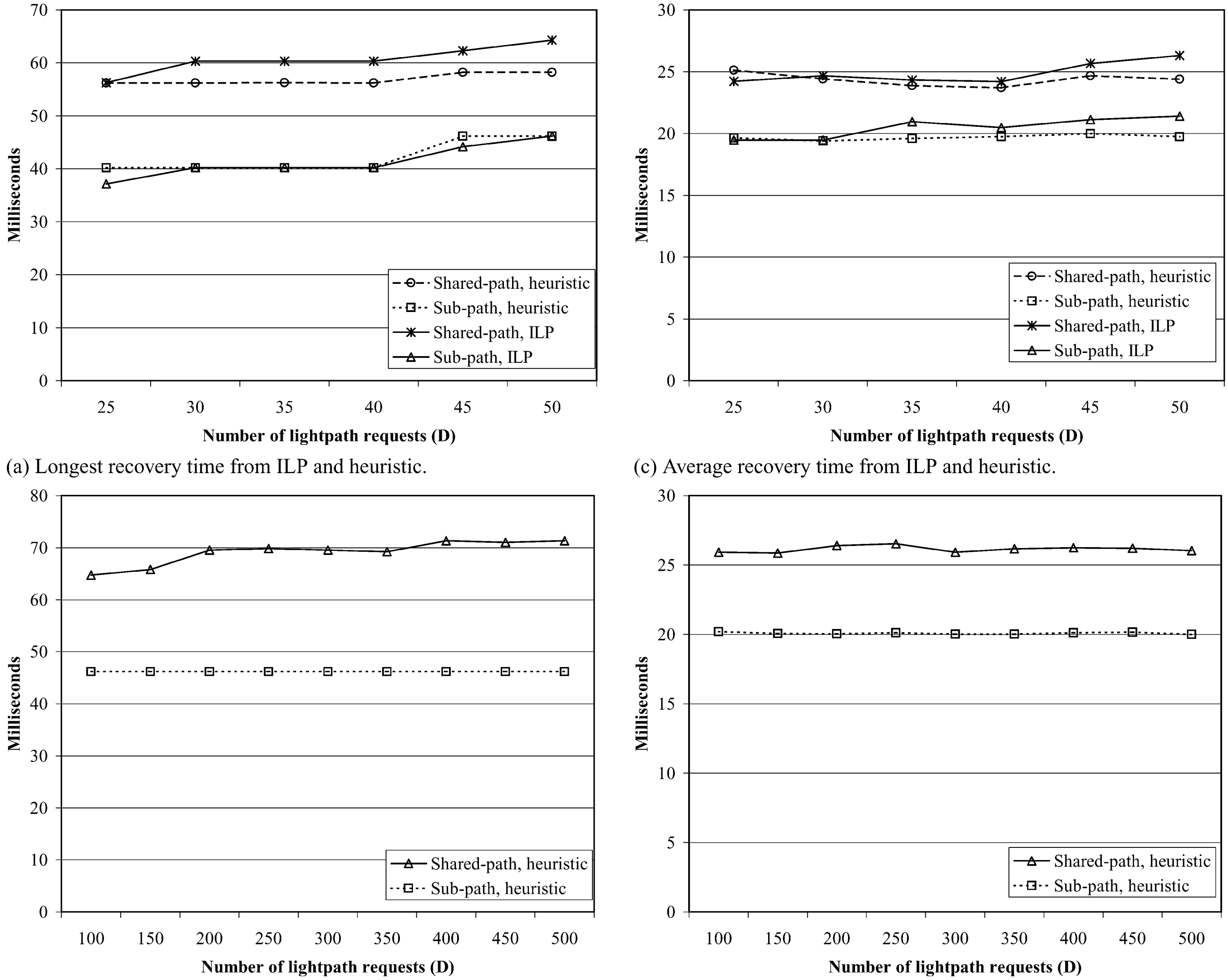
We compare the recovery time, survivability, scalability, and resource utilization of subpath protection with those of shared-path protection by applying the split ILP and the heuristic to the network in Fig. 1. (We remark that shared-link protection is much less resource efficient than shared-path protection [6], [8]; thus, shared-link protection is not compared to subpath protection in this study.) Shared-path protection is a special case of subpath protection when the number of domains is one, and the results for shared-path protection are obtained by treating the entire network as one domain.

Please note that the fact that the DBNs are wavelength convertible under subpath protection while the corresponding nodes are wavelength continuous under shared-path protection does not bias the results much *under a nonblocking model*. While wavelength-conversion capability at DBNs is critical to simplify algorithm design and to achieve management convenience for subpath protection, wavelength-conversion capability at the corresponding nodes plays a much less important role for shared-path protection under a nonblocking model. The underlying assumption for a nonblocking model is that all the lightpath requests can be satisfied. This implies that sufficient number of wavelengths exists. As a result, the need for wavelength converters is small. For example, if a lightpath request needs to traverse a wavelength convertible node to convert from wavelength λ_1 to λ_2, chances are that this lightpath request may be routed using a different wavelength λ_6. However, it is valid that the existence of a few wavelength converters may slightly reduce the number of wavelengths for shared-path protection.

A. Recovery Time

The recovery time[7] of link $\langle i, j \rangle$ with respect to a lightpath between node-pair (s, d), T_{ij}^{sd}, is defined as the time period over which data on the (s, d) lightpath is lost due to the failure of

[7]Note that the recovery time here is similar to the protection-switching time defined in [6] and the restoration speed defined in [4], but it has some improvements, e.g., pipelining the switch configurations.



(a) Longest recovery time from ILP and heuristic.

(b) Longest recovery time from heuristic.

(c) Average recovery time from ILP and heuristic.

(d) Average recovery time from heuristic.

Fig. 4. Recovery-time comparison between subpath and shared-path protection schemes.

link $\langle i,j \rangle$. We use the following notations to derive the general formula of T_{ij}^{sd} for shared-path protection:

- d_{is} propagation delay from node i to node s;
- h_{is} number of hops from node i to node s;
- h_b number of hops on the backup path between node pair (s,d);
- F failure-detection time;
- X crossconnect-configuration time
- M message-processing time (including queueing delay) at a node.

First, consider the time period d_{is} right before link $\langle i,j \rangle$ fails. Node s has been sending data, which will be lost when link $\langle i,j \rangle$ fails. Second, upon detecting a link failure, node i sends[8] 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 $X+(h_b+1)\times M$ before it switches to the backup route (configuring the crossconnects can be done in parallel). In summary

$$T_{ij}^{sd} = F + 2 \times d_{is} + (h_{is}+1) \times M + X + (h_b+1) \times M.$$

The recovery time of link $\langle i,j \rangle$, T_{ij}, is the recovery time averaged over all the lightpaths that traverse $\langle i,j \rangle$, i.e., $T_{ij} = (\sum_{(s,d)\in\Gamma} T_{ij}^{sd})/|\Gamma|$, where Γ is the set of lightpaths whose primary paths traverse $\langle i,j \rangle$. The network-wide *average recovery time*, T, is defined as the summation of the probability[9] that link $\langle i,j \rangle$ fails (with probability p_{ij}) times the recovery time of link $\langle i,j \rangle$, i.e., $T = \sum_{\langle i,j\rangle\in E} p_{ij} \times T_{ij}$. The network-wide *longest recovery time* is the maximum of T_{ij}^{sd} over all possible (s,d) and $\langle i,j \rangle$ combinations.

Under subpath protection, the recovery time is defined the same as above for an intradomain lightpath request. For an interdomain lightpath request, the recovery-time calculation is carried out for each segmented intradomain subpath.

[8]We assume that there is a separate packet-based control plane, which has the same topology as the network we are considering. A packet sent on the control plane follows the shortest path between the source and destination nodes.

[9]The probability that a fiber fails is proportional to the length of the fiber [32].

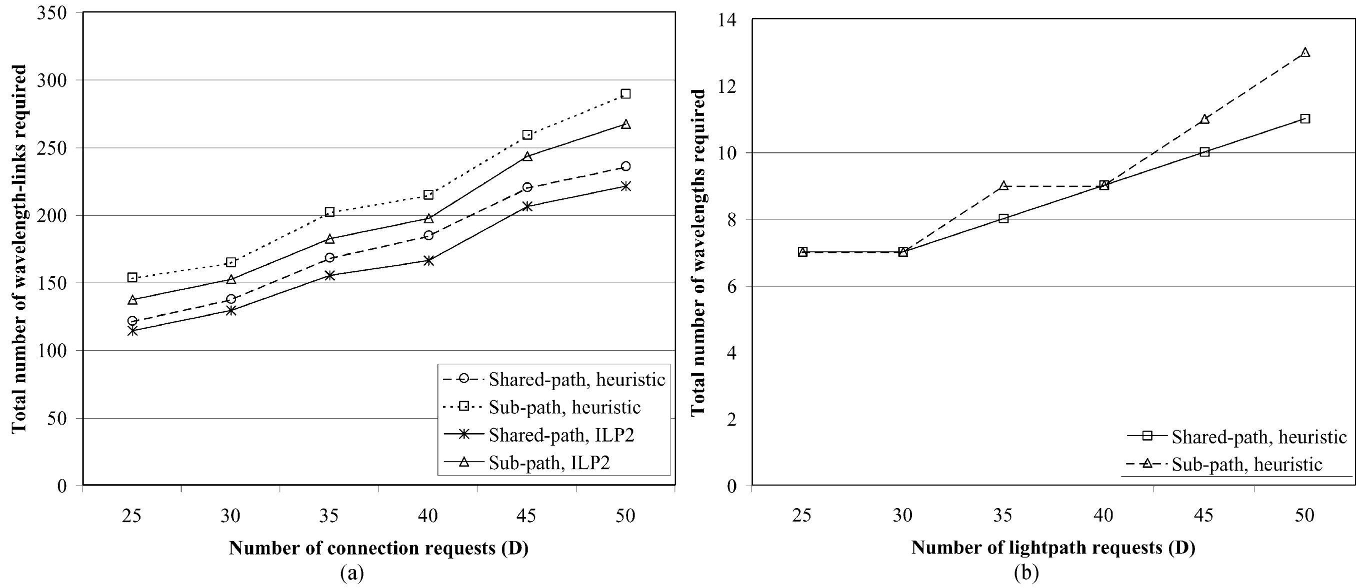


Fig. 5. Resource-utilization comparison. (a) Number of wavelength-links. (b) Number of wavelengths.

For our numerical examples, we assume $F = 10\ \mu$s, $X = 5$ ms, and $M = 20\ \mu$s, which appear to be consistent with current technologies. Fig. 4 demonstrates that subpath protection reduces both the network-wide longest recovery time and the average recovery time significantly, e.g., in this example, it reduces average recovery time by 14% (for $D = 40$) to 24% (for $D = 250$), as shown in Fig. 4(c) and (d), and longest recovery time by 28% (for $D = 50$) to 35% (for $D = 500$), as shown in Fig. 4(a) and (b). We observe from our results that the link propagation delay dominates recovery time. Thus, when the size of the network increases, the recovery time of shared-path protection will increase accordingly since the total mileage of the fiber-disjoint path pair increases. The recovery time of subpath protection, however, will remain relatively constant since we can keep the size of each domain modest by increasing the number of domains. Even if the size of the network remains the same, the longest recovery time for shared-path protection increases gradually when the number of lightpath requests increases, as shown in Fig. 4(b), while the longest recovery time for subpath protection remains relatively constant. This is because when the number of lightpaths increases, more backup paths are likely to share wavelength links. This increased backup sharing leads to longer backup paths [41]. Since subpath protection has a much smaller upper bound on the domain diameter compared to the upper bound on the network diameter, it has a much smaller upper bound on recovery time. Note that, under subpath protection, the longest recovery time is below 50 ms in all the cases. Thus, it may now be possible to guarantee the 50-ms recovery time (as SONET ring does) in large mesh networks by properly partitioning the network and applying subpath protection.

B. Survivability

Survivability refers to the types of failures a proposed scheme can handle: link, node, or multiple failures (which [4] refers to as restorability). Shared-path protection [6] handles single-link failures by using fiber-disjoint path pairs [6], [12], [42], and single-node failure by using node-disjoint path pairs [2], [24], not multiple failures. Subpath protection combats against single-link failures the same way as shared-path protection does as shown in the split ILP. Subpath protection can also handle non-DBN failures by finding node-disjoint path pairs and DBN failures by the approach in Section II-C.

An improvement on survivability over shared-path protection is that subpath protection can survive up to $|\mathcal{P}|$ failures as long as there is only one failure per domain because, due to the autonomous property of domains, subpaths of the same lightpath are treated independent of one another.

C. Scalability

We consider scalability from the network control and management perspective. For network control, as pointed out in [2], any mesh protection scheme needs to maintain large distributed routing tables. However, under subpath protection, a non-DBN node only needs to maintain state information about the domain it belongs to, and a DBN node needs to maintain state information about the domains it belongs to and the summarized connectivity information between DBNs (compared to the state information of the entire network). Signaling is another important aspect of network control. Under subpath protection, local signaling information is filtered at DBNs and will not be disseminated to other domains. For example, subpath protection limits fault propagation within the scope of a domain (compared to the entire network in shared-path protection) and, after a fault occurs, protection switching, the process used by the source node of an affected lightpath to signal the destination node to switch to the backup path, happens within the scope of a domain (compared to the entire network). Thus, it reduces protection-switching time (as shown in Section V-A) and saves control bandwidth as well.

For network management, networks of modest size need facility management systems (FMS) to monitor network state, to localize fault, and to provide billing and other capabilities. In

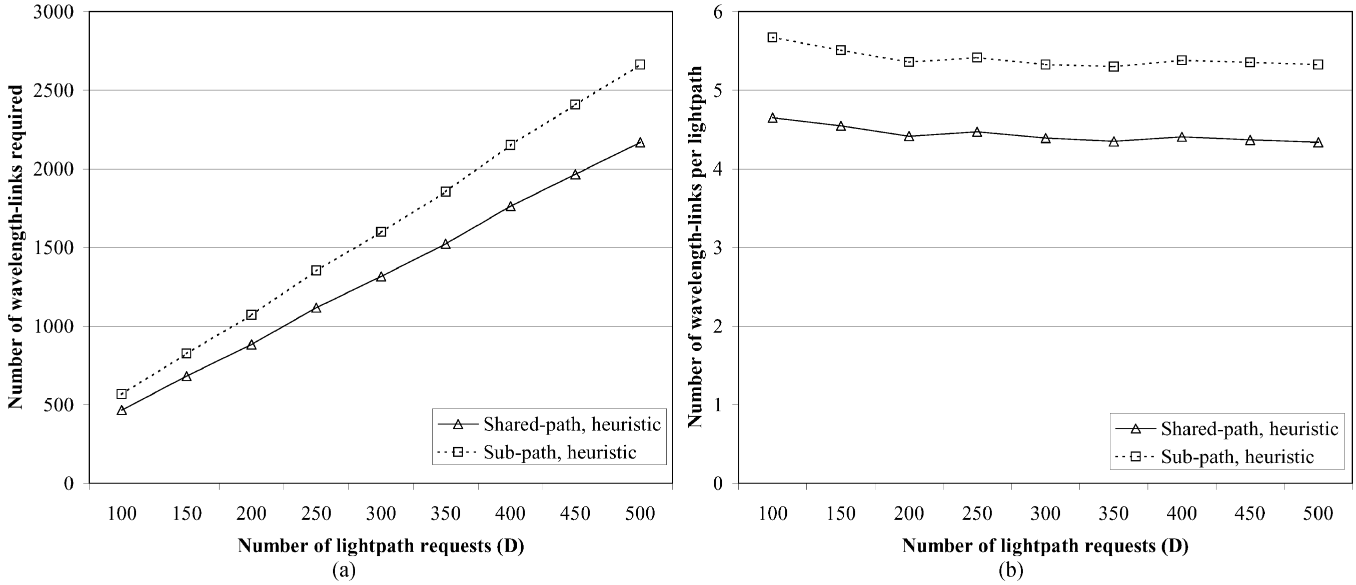


Fig. 6. Resource-utilization comparison: number of wavelength-links used (a) for all the lightpaths and (b) per lightpath.

the absence of administrative domains, how the FMS for the entire network keeps pace with the growth of the network becomes questionable, as has been witnessed by carriers [26]. Under subpath protection, each domain has its own FMS, and the function of managing the entire network is distributed to each domain. Furthermore, fault localization is limited to the scope of a domain (compared to the entire network in the absence of domains). As a result, the mean time to repair will be reduced and the overall network reliability can be improved [43].

In summary, domain partitioning hides information from all nodes and leads to improved scalability. This information hiding is essential to scalability, as has been justified by IP networks, which work as a collection of autonomous systems further divided into Interior Gateway Protocol (IGP) areas, such as OSPF and IS-IS areas.

D. Resource Utilization

Fig. 5(a) compares the total number of wavelength-links required for subpath protection with that of shared-path protection by applying the split ILP and the heuristic to the network shown in Fig. 1 with six sets of randomly generated lightpath requests. We observe that subpath protection requires more resources, e.g., it sacrifices network resource utilization by 17% (for $D = 35$) to 21% (for $D = 50$) from the ILPs results in this example. This is expected since subpath protection has the domain constraints C.5–C.6 in addition to the shared-path-protection constraints C.1–C.4. The second observation is that the heuristic performs close to the split ILP for both shared-path protection and subpath protection. Fig. 5(b) also shows a similar trend for the total number of wavelengths required. Thus, we use the heuristic to compare the resource utilization of subpath protection with that of shared-path protection for a large number of lightpath requests.

Fig. 6 plots the total number of wavelength-links required for subpath protection to that of shared-path protection by applying the heuristic to the network in Fig. 1 with nine sets of randomly generated lightpath requests (the number of lightpaths, D, ranges from 100 to 500). While the difference between the total number of wavelength-links used by subpath protection and shared-path protection increases as D increases, as shown in Fig. 6(a), the difference between the number of wavelength-links used per lightpath remains relatively constant, as shown in Fig. 6(b). This means that the amount of resources sacrificed due to domain constraints is proportional to the number of lightpaths. Fig. 6(b) also illustrates the advantage of backup sharing: the number of wavelength-links per lightpath in both shared-path protection and subpath protection decreases as the number of lightpaths increases.

A counter-intuitive observation is that subpath protection may sometimes require *less* resources than shared-path protection, as shown in Appendix IV.

VI. Conclusion and Future Work

We proposed and investigated subpath protection for survivable lightpath provisioning and fast protection switching in optical WDM mesh networks. The main ideas of subpath protection are to partition a large optical network into smaller domains, and to apply shared-path protection to the optical network while guaranteeing the autonomy of each domain. We proved that the RWA problem under shared-path protection for a given set of lightpath requests is NP-complete (even if the number of wavelength on each link is one), so is the problem of RWA under subpath protection for a given set of lightpath requests since the former is a special case of the latter. Furthermore, we proved that the problem of finding optimal backup paths, under shared-path-protection constraints (or subpath-protection constraints) for a set of lightpath requests whose primary paths are given, is still NP-complete. We mathematically formulated the RWA problem with subpath-protection constraints for a given set of lightpath requests and developed a heuristic to find efficient solutions. While subpath protection reduces the ability to find globally optimal solution due to domain partitioning, it increases backup sharing. The comparisons between subpath

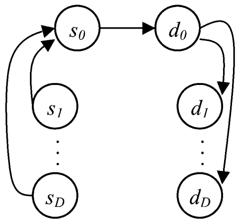


Fig. 7. Construction of NP-complete proof.

protection and shared-path protection on a nationwide network with dozens of wavelengths per fiber show that, for a modest sacrifice in resource utilization, subpath protection achieves improved survivability, much higher scalability, and significantly reduced fault-recovery time.

Please note that the performance of our subpath protection largely depends on how a network is partitioned. The significant benefits-shorter recovery time and higher scalability-of subpath protection come from the fact that the network is well partitioned. In our example, we chose the network partitions based on geography. In general, how to partition a network may depend on the topology and involve administrative issues. As a result, how to properly partition a network is expected to be a challenging problem and is left open for future research.

APPENDIX I
NP-COMPLETENESS OF RWA UNDER SHARED-PATH-PROTECTION CONSTRAINTS

Proof of Theorem 1

We reduce the known NP-complete problem, multisource multidestination edge-disjoint paths problem [44] (MSMDED), to RWASPP. The decision version of MSMDED is stated as follows.

Instance: A graph $G = (V, E)$, and a set of D node pairs $(s_1, d_1), \ldots, (s_D, d_D)$ (D is an input).

Question: Is there a set of D mutually link-disjoint paths, one for each node pair?

It is easy to see that RWASPP $\in$ NP since a nondeterministic algorithm can guess a link-disjoint path pair for each node pair and check in polynomial time if the D link-disjoint path pairs found satisfy constraints C.1–C.4 (in Section II-D).

We reduce MSMDED to RWASPP. Let $\tilde{G} = (\tilde{V}, \tilde{E})$, $\tilde{\mathcal{D}} = \{(s_k, d_k) | 1 \leq k \leq D, s_k, d_k \in \tilde{V}\}$ be an arbitrary instance of MSMDED. Construct an instance of RWASPP as follows: $W = 1$, $\mathcal{D} = \tilde{\mathcal{D}}$, and $G = (V, E)$, where $V = \tilde{V} \cup \{s_0, d_0\}(s_0, d_0 \notin \tilde{V})$, $E = \tilde{E} \cup \{\langle s_k, s_0\rangle | 1 \leq k \leq D\} \cup \{\langle s_0, d_0\rangle\} \cup \{\langle d_0, d_k\rangle | 1 \leq k \leq D\}$ (please refer to Fig. 7). Clearly, the construction can be accomplished in polynomial time.

Suppose there exist D mutually link-disjoint paths—$\tilde{p_1}, \ldots, \tilde{p}_D$, one for each node pair—in the instance of MSMDED. We construct the set of D link-disjoint path pairs, (p_p^k, p_b^k), as follows (please note that there is only one wavelength):

$$p_p^k = \tilde{p_k}, \quad p_b^k = \langle s_k, s_0, d_0, d_k\rangle \quad \forall\, 1 \leq k \leq D.$$

Then, Constraints C.1, C.2, and C.4 are satisfied since the set of paths $\{p_p^k \mid 1 \leq k \leq D\}$ is mutually link-disjoint; and Constraint C.3 is satisfied because backup paths use links only in E, not in $\tilde{E}$. Thus, the set of path pairs so constructed is a feasible solution to RWASPP.

Suppose the instance of RWASPP has a set of D link-disjoint path pairs, $\{(p_w^k, p_b^k) | 1 \leq k \leq D\}$, which satisfies Constraints C.1–C.4. Consider link $\langle s_0, d_0\rangle$. It can be in only one of the following two states.

1) *Link $\langle s_0, d_0\rangle$ is used by some primary path p_p^j.* Then, only p_p^j uses $\langle s_0, d_0\rangle$ since $W = 1$. Construct the set of D paths in $\tilde{G}$ as follows:

$$\tilde{p_k} = \begin{cases} p_p^k, & \text{if } k \neq j \\ p_b^k, & \text{if } k = j \end{cases} \qquad \forall\, 1 \leq k \leq D.$$

Clearly, there is one path for each node pair; by Constraint C.2, $\tilde{p_1}, \ldots, \tilde{p}_{j-1}, \tilde{p}_{j+1}, \ldots, \tilde{p}_D$, are mutually link-disjoint since $W = 1$; and by Constraint C.3, $\tilde{p_1}, \ldots, \tilde{p}_{j-1}, \tilde{p}_j, \tilde{p}_{j+1}, \ldots, \tilde{p}_D$ are mutually link-disjoint. Thus, the set of paths $\{\tilde{p_k} | 1 \leq k \leq D\}$ so found is a feasible solution to MSMDED.

2) *Link $\langle s_0, d_0\rangle$ is not used by any primary path.* Let $\tilde{p_k} = p_p^k$. Then, there is one path for each node pair. By Constraint C.2, the set of paths $\{\tilde{p_k} \mid 1 \leq k \leq D\}$ is mutually link-disjoint because $W = 1$. Thus, the set of paths $\{p_k | 1 \leq k \leq D\}$ so found is a feasible solution to MSMDED.

This concludes our proof that RWA under shared-path-protection constraints is NP-complete. Thus, RWA under subpath protection is also NP-complete since the former is a special case of the latter when the number of partitions, $|\mathcal{P}|$, is one.

APPENDIX II
NP-COMPLETENESS OF OBR

A. Proof of Theorem 2

We reduce the directed Steiner minimal tree (DSMT) problem, which is NP-complete [45], to OBR. The decision version of the DSMT problem is defined as follows.

DSMT: Given a weighted, directed graph $G = (V, E, C)$, a set of nodes $\tilde{V} \subset V$, an integer c, and a source node $s \notin \tilde{V}$, does there exist a directed Steiner tree (DST) $\mathcal{T}$ such that there exists a directed path in $\mathcal{T}$ from s to every vertex in $\tilde{V}$, and the cost of $\mathcal{T}$, $C(\mathcal{T})$, is no more than c?

OBR $\in$ NP since a nondeterministic algorithm can guess a backup path for each lightpath and check in polynomial time if the primary and backup paths satisfy Constraints C.1–C.4 (in Section II-D) and the cost of all the backup paths is no more than c.

Given an arbitrary instance of DSMT $G = (V, E, C)$, $\tilde{V}$, and c, construct an instance of OBR $G' = (V', E', C')$, $W = 1$, $\mathcal{D}$, and p_p^k as follows (let $D = |\tilde{V}|$):

$$\begin{aligned} V' &= V \cup \{z_1, \ldots, z_D\} \\ E' &= E \cup \{sz_k \mid \forall\, 1 \leq k \leq D\} \cup \{z_k d_k \mid \forall\, d_k \in \tilde{V}\} \\ C'(ij) &= \begin{cases} C(ij), & \text{if } ij \in E \\ 0, & \text{otherwise} \end{cases} \\ \mathcal{D} &= \{(s, d_k) \mid \forall\, d_k \in \tilde{V}\} \\ p_p^k &= \langle s, z_k, d_k\rangle \quad \forall\, d_k \in \tilde{V}. \end{aligned}$$

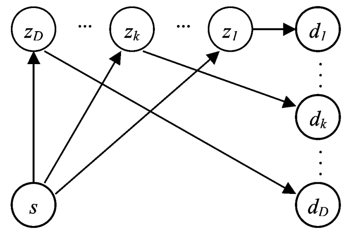


Fig. 8. Reduce DSMT to OBR.

This construction is shown in Fig. 8. Clearly, the transformation can be done in polynomial time.

Suppose the instance of DSMT can find a DST $\mathcal{T}$ of cost no more than c. Let the backup path of lightpath k, p_b^k, be the path from s to d_k, using links only in $\mathcal{T}$. First, Constraints C.1–C.4 are satisfied since primary paths only use newly added links and none of the two primary paths traverse any common link; thus, the backup paths can share any wavelength along any link in E. Second, the set of backup paths so found has cost no more than c. Thus, the set of backup paths so found is a feasible solution for OBR.

Suppose the instance of OBR can find a set of backup paths, $\{p_b^k | \forall\ 1 \leq k \leq D\}$, such that it has cost no more than c. If $\{p_b^k\}$ forms a tree, then the tree so formed is a feasible solution for DSMT. Otherwise, we can repeatedly remove a link (which is of nonnegative cost) from the set of links used by $\{p_b^k\}$ until it forms a tree rooted at s, then the tree so formed is a feasible solution to DSMT, and it has cost no more than c.

This concludes our proof that OBR is NP-complete.

Appendix III
Correctness of the Heuristic

We prove the correctness of the heuristic as follows. Let $H(G, W, \mathcal{P}, \mathcal{D})$ be the solution given by the heuristic, and let $H_i(G, W, \mathcal{P}, \mathcal{D})$ be the intermediate result given by Phase i ($i = 1, 2, 3$). We first prove that $H_1(G, W, \mathcal{P}, \mathcal{D})$ is correct with respect to routing under domain constraints and fiber-disjoint constraints; then we prove that $H_2(G, W, \mathcal{P}, \mathcal{D})$ is correct with respect to routing and wavelength assignment under subpath-protection constraints (C.1–C.6 in Section II-D), and $H_3(G, W, \mathcal{P}, \mathcal{D})$ maintains correctness.

Claim 1: The path pair (p_p^k, p_b^k) for lightpath k given by $H_1(G, W, \mathcal{P}, \mathcal{D})$ satisfies the following.

1) p_p^k and p_b^k are fiber-disjoint.
2) p_p^k and p_b^k do not use resources of other domains if k is an intradomain lightpath; p_p^k and p_b^k exit one domain (and enter another domain) through a common DBN if k is an interdomain lightpath.
3) The total cost of p_p^k and p_b^k is minimal among all such pairs.

Proof: If k is an intradomain lightpath, then Conditions 1 and 3 follow directly from the proof given in [36], and Condition 2 is true because the heuristic is carried out in the domain k_s and k_d belong to. Hereafter, we assume that k is an interdomain lightpath request, and we let p_s^k be the shortest path found by $H_1(G, W, \mathcal{P}, \mathcal{D})$ in G_a^k. We prove the claim for an interdomain lightpath as follows.

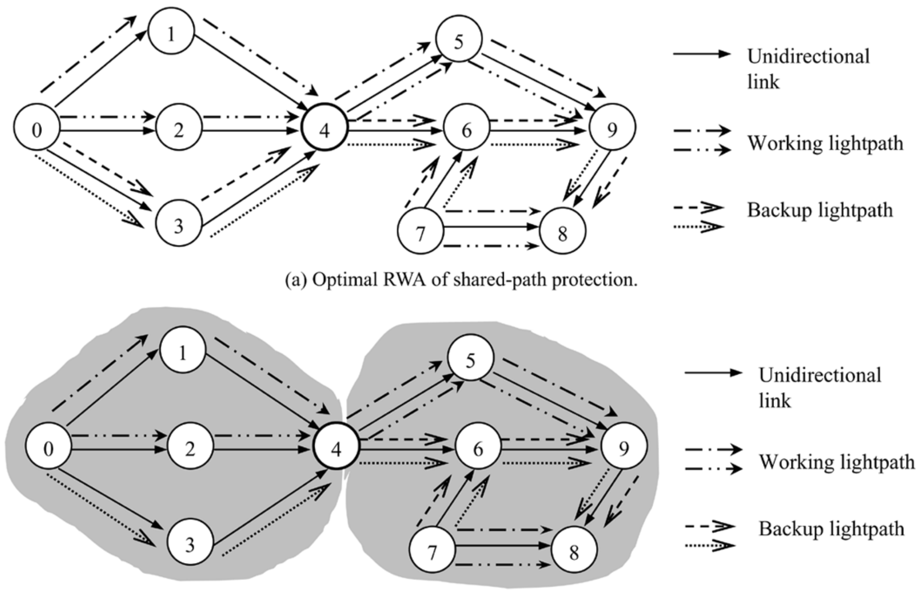
1) Suppose p_p^k and p_b^k are not fiber-disjoint. By the construction of G_a^k, p_s^k must use at least two links (in G_a^k) whose corresponding fiber-disjoint path pairs in G are in the same domain because domains do not share any link (please note that any link p_s^k traverses in G_a^k corresponds to two fiber-disjoint paths in G). Let $\langle r_i, r_j \rangle$ and $\langle r_x, r_y \rangle$ be two such links. Then r_i, r_j, r_x, r_y must be in the same domain; otherwise, their corresponding fiber-disjoint path pairs will not be in the same domain. Without loss of generality, assume that p_s^k traverses link $\langle r_x, r_y \rangle$ after $\langle r_i, r_j \rangle$, i.e., p_s^k is of the form $\langle k_s, \ldots, r_i, r_j, \ldots, r_x, r_y, \ldots, k_d \rangle$. By the construction of G_a^k, the link $\langle r_i, r_y \rangle$ has less cost than the path $\langle r_i, r_j, \ldots, r_x, r_y \rangle$; thus, $\langle k_s, \ldots, r_i, r_y, \ldots, k_d \rangle$ has less cost than p_s^k. This contradicts that p_s^k is the shortest path. Thus, p_p^k and p_b^k are fiber-disjoint.
2) By the construction of G_a^k, each link along p_s^k corresponds to a fiber-disjoint path pair in G, and the path pair (p_p^k, p_b^k) is formed by concatenating all such fiber-disjoint path pairs. That p_p^k and p_b^k exit one domain (and enter another domain) through a common DBN follows since V_a^k includes only DBNs, k_s, and k_d.
3) This condition holds because segments of a shortest path are shortest subpaths [46], and the fiber-disjoint path pair found in a domain using Suurballe's algorithm is the shortest among all such pairs in that domain [36].

■

The solution given by $H_2(G, W, \mathcal{P}, \mathcal{D})$ satisfies domain constraints (C.5–C.6 in Section II-D) because Phase 2 works on a per-domain basis. The solution given by $H_2(G, W, \mathcal{P}, \mathcal{D})$ satisfying shared-path-protection constraints (C.1–C.4 in Section II-D) follows from the construction of G_c (defined in Section IV-B) and the correctness of the sequential coloring algorithm. The solution given by $H_3(G, W, \mathcal{P}, \mathcal{D})$ maintaining correctness follows from the definition of the wavelength-link cost function and the correctness of shortest-path algorithm [46].

Appendix IV
Subpath Outperforms Shared Path: An Example

Fig. 9 illustrates one such example. The 10-node network has two wavelengths per fiber, and it needs to carry two lightpath requests between node pair $(7, 8)$ and another two lightpath requests between node pair $(0, 9)$. In both cases, the two lightpaths between node pair $(7, 8)$ will use the only two wavelengths on link $\langle 6, 9 \rangle$ because there is only one fiber-disjoint path pair between node pair $(7, 8)$ ($\langle 7, 8 \rangle$ and $\langle 7, 6, 9, 8 \rangle$). If any of the two wavelengths on link $\langle 6, 9 \rangle$ is used by a primary path between node pair $(7, 8)$, then there is no fiber-disjoint path pair for one of the lightpaths between node pair $(0, 9)$. Thus, the two wavelengths on link $\langle 6, 9 \rangle$ can only be used by backup paths, and the two primary paths between node pair $(0, 9)$ need to traverse both links $\langle 4, 5 \rangle$ and $\langle 5, 9 \rangle$. Under share-path protection, the two backup paths between node pair $(0, 9)$ cannot share any wavelength along the entire paths because their corresponding primary paths between node pair $(0, 9)$ both traverse



(a) Optimal RWA of shared-path protection.

(b) Optimal RWA of sub-path protection. Each cloud denotes a domain.

Fig. 9. Subpath protection outperforms shared-path protection in terms of resource utilization (note the difference along path $\langle 0,3,4 \rangle$.) Node 4 is wavelength convertible.

links $\langle 4,5 \rangle$ and $\langle 5,9 \rangle$). Under subpath protection, node 4 segments each primary path between node pair $(0,9)$ into two subpaths (one in each domain). The fact that the two primary subpaths in the right domain are not mutually diverse does not affect the two primary subpaths in the left domain. As a result, the backup subpaths for the two primary subpaths in the left domain share the wavelengths along the entire paths because the two primary subpaths in the left domain are fiber-disjoint. Hence, the optimal solution for the RWA under shared-path-protection constraints requires two more wavelength-links (along path $\langle 0,3,4 \rangle$) than the optimal solution for the RWA under subpath-protection constraints.

The rationale behind this property is that each subpath is independent of the other subpaths of the same lightpath. (Please refer to the example in Section II-A.) This gain is achieved by the domain constraints, namely, the primary and backup paths of an interdomain lightpath exit a domain (and enter another domain) through a common DBN and an intradomain lightpath cannot use resource of other domains. As the size of the network or the number of lightpath requests increases, the correlation between backup paths (two backup paths cannot share wavelength if their corresponding primary paths are not mutually diverse) can become noticeable or even significant. Subpath protection reduces this correlation by segmenting a long lightpath into several shorter ones, thus it increases the potential sharing between backup paths. Then, it would be expected that the difference in the number of wavelength-links per lightpath between subpath protection and shared-path protection decreases as the number of lightpaths increases. The reason Fig. 6(b) does not show this trend is that we assume a nonblocking model, i.e., all the lightpath requests can be routed (the number of wavelengths on each link is large). The situation in Fig. 9 will not be the case if we have one more wavelength on each link. Thus, this increased backup sharing is more likely to happen when the network load is high.

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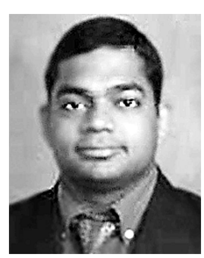

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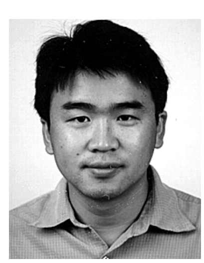

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