Coordinated Survivability in IP-over-Optical Networks with IP-Layer Dual-Homing and Optical-Layer Protection

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Abstract— **Dual homing is a fault-tolerance mechanism generally used in IP-based access networks to increase the survivability of the network. In a dual-homing architecture, a host is connected to two different access routers; therefore, it is unlikely that the host will be denied access to the network as the result of a failure in the access network, a failure of the access router, or congestion at the access router. However, dual homing cannot provide survivability with respect to possible failures in the optical core network. To provide survivability in the core network, optical *protection* and *restoration* techniques must be used. In the past, dual homing architectures and optical protection schemes have been studied independently of one another. This paper studies coordinated multi-layer survivability techniques that use both dual-homing schemes and optical protection schemes in an IP-based access network over a WDM-based optical core network. Specifically, we investigate the protection design problem in the WDM core network, given that a dual-homing infrastructure is implemented in the access network. Several solutions are proposed, and it is shown that the proposed coordinated survivability schemes can reduce cost compared to the case in which the survivability mechanisms are not coordinated between the IP layer and the optical layer.**

Keywords: IP, WDM, Dual homing, Lightpath, Survivability, and Protection

I. Introduction

As the amount of critical traffic carried over the Internet continues to grow, the problem of providing reliable and survivable connectivity becomes increasingly important. The next-generation Internet is expected to be deployed over an optical wavelength division multiplexing (WDM) backbone network; thus, survivability issues must be considered at the optical layer as well as the IP layer.

In the optical WDM layer, each fiber link is capable of carrying multiple channels. If optical crossconnects are deployed in the network, it becomes possible to establish optical circuit-switched paths, or lightpaths, end-to-end across the optical core. When a failure occurs in the network, the network must continue to support the traffic carried on all lightpaths. One method for providing survivability is through protection schemes. In protection schemes, back-up resources are allocated and reserved for each connection in the network. One type of protection scheme is *path protection*, in which resources are reserved along a link-disjoint back-up path for each primary path in the network. In the event that a link on the primary path fails, traffic will be re-routed along the back-up path. The back-up path must be link-disjoint from the primary path in order to ensure that a single link failure will not simultaneously disrupt both the primary and back-up paths. In such a scheme, all working traffic is protected against any single link failure in the network. The back-up resources may be shared among multiple primary paths as long as the primary paths do not share any links. Such an approach is referred to as *shared protection* [1], [2].

At the IP layer, *dual homing* can be used to increase survivability in the access network. In a dual homing architecture, a host in the access network is attached to two IP routers, called *dual homes*. These routers, in turn, are connected to underlying edge optical cross connects (OXCs) of the core network, as shown in Fig. 1. In the event of a failure in the access network or congestion at the access router, the dual-homing scheme enables the access traffic to be shifted from the current access router to the other access router. The main objective of dual homing is to provide enhanced survivability to protect against node and link failures in the access network. Dual homing can also be used to protect against congestion at one of the access routers. Dual-homing architecture design has been extensively studied in self-healing ring networks [3], [4], [5], [6], [7].

A number of works addresses multi-layer survivability in IP over WDM networks [8], [9], [10], [11], [12], [13]. In [8], the authors compare optical-layer protection to IP-layer restoration in terms of required backup capacity and restoration time. In [9], [10], [11], various multi-layer survivability strategies that coordinate optical-layer protection and IP layer protection and restoration are discussed. The work in [12] considers optical layer protection and IP-layer dual homing. Different degrees of coordination between the IP layer and the optical layer are considered, and it is shown that a higher degree of coordination between layers results in lower cost. In [13], the authors consider the problem of supporting dual-homing in passive optical networks.

There have been several efforts on providing sur-

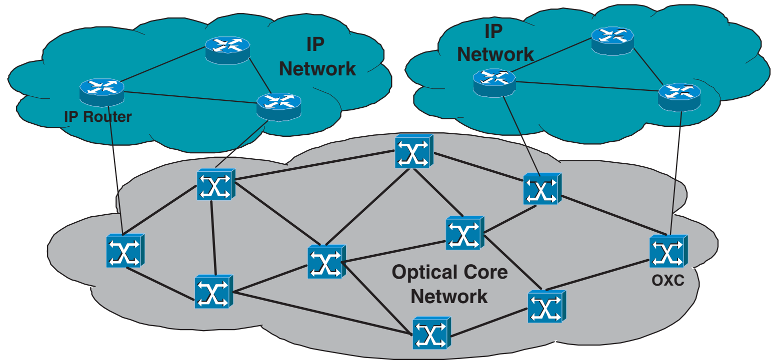


Fig. 1. IP-over-WDM Dual-homing network architecture.

vivability for a dual-homed IP-based access network over a WDM-based core network [13], [12]. All these studies consider providing survivability separately at the IP layer and the WDM layer. In [13], the authors discuss how to support dual-homing in passive optical networks; while [12] studies survivability in IP-over-WDM networks and provides different protection types (unprotected, protected, and dual homing) for each IP link in order to keep the networks connected in the event of a link failure. The focus of our paper is to provide an coordinated solution for providing survivability in an IP-over-WDM mesh network.

The focus of this paper is to provide an coordinated solution for providing survivability in an IP-over-WDM mesh network. Dual homing is assumed to provide survivability against a node or link failure in the access network, while an optical protection scheme provides survivability against a single link failure in the optical core network. In [18] and [19], we considered the problem of protection in the optical core network given that dual-homing protection is implemented at the source access network. In this paper, we extend our previous work by considering the case in which dual-homing protection is implemented at both the source and destination access networks. We consider a generalized failure scenario in which independent failures may occurs simultaneously in the source access network, the destination access network, and the optical core network. Note that while the probability of simultaneous equipment or fiber failure may be small, it is possible that the IP access routers may experience congestion, in which case, dual homing may enable an IP host to switch to a different access router. By considering the dual-homed IP-over-WDM architecture (Fig. 1), we observe that, at any given time, each host transmits data to the destination only through one of the dual homes in the source access network and one of the dual homes in the destination access network. Based on this observation, we see that only one of the primary-backup-path pairs between the source dual homes and the destination dual homes will be utilized at any given time. This property leads to fewer restrictions on the disjointness constraint between the two primary and two backup paths from each of the source dual homes to the destination dual homes. We observe that by providing an integrated solution for protection in the optical layer with knowledge of dual homing at the IP layer, we can obtain significant cost benefits compared to handling survivability separately at each of the layers (IP and WDM).

The rest of the paper is organized as follows. The network architecture of dual-homing protection problem is presented in Section II. Several heuristic algorithms for dual-homing protection problem are presented in Section III. In Section IV, we evaluate the performance of all the proposed algorithms. Finally, the conclusion and future work are presented in Section V.

II. Problem Description

In this section, we describe the different possible failure scenarios and describe the coordinated protection problem for IP-over-optical networks. Consider two IP access networks that are connected to each other through an optical core network. In this IP-over-optical network, failures may occur in the IP access networks or in the optical core network. If we observe carefully, we have three different layers in the end-to-end IP-over-Optical network, i.e., the source IP access network, the optical core network, and the destination IP access network. The system consists of three independent layers that can be prone to failure.

We consider an IP-over-optical network as shown in Fig. 2(a), where a source IP host is attached to two IP routers (homes) in the IP-based source access network through link-disjoint paths. Each IP router is connected to an optical cross connect (OXC), which in turn is linked to other OXCs that constitute the all-optical core network. The optical core network provides direct logical connections between IP access routers at the edge of the network. At the destination, the destination IP host may also be connected to two edge IP routers in the destination IP access network. In this example, there is only one unprotected path between any pair of edge routers.

In the generalized failure scenario, a single node or link failure may occur in either the IP access networks, or in the optical core network. We assume that each network can have at most a single failure, but that failures in different networks may occur simultaneously. In general, solutions for node failures will also cover link failures.

There are several failure scenarios that are of practical interest. Specifically, we consider the simultaneous failure of a node (or link) in each of the three networks (source IP access, optical core, and destination IP access). In this situation, both the source and destination IP-based access networks should support a dual-homing architecture, and the optical core network should provision link-disjoint paths between any two source IP routers and two destination IP routers (dual homes). Figure 2(a) shows an architecture that supports two simultaneous access node failures, but is susceptible to core link failures. The problem of calculating the least-cost primary and protection paths in the core network so as to handle core link failures is conjectured to be NP-hard for both static and dynamic connection requests.

The problem can be formally defined as follows. A WDM network can be modeled as an unidirected graph $G =< V, E >$, where V is the set of OXCs and E is the set of WDM links. Let the wavelength cost of a WDM link $e \in E$ be $c(e)$. Let the maximum number of wavelengths in each link be W. Let R be the set of all connection requests in G, and let each individual connection request, denoted by k, be given by $\{\{s_1^k, s_2^k\}, \{d_1^k, d_2^k\}\}$, where s_1^k and s_2^k are two OXCs connected to the dual-homed source access IP routers, and d_1^k and d_2^k are two OXCs connected to the dual-homed destination access IP routers that connects to the destination host of connection request k. For a given k, how to determine the dual homes is studied in [20]. In this paper, we assume that s_1^k, s_2^k, d_1^k, and d_2^k are given for each k and concentrate on routing the primary and backup lightpaths from s_1^k to d_1^k and s_1^k to d_2^k as well as from s_2^k to d_1^k and s_2^k to d_2^k. Let the primary lightpaths from s_1^k to d_1^k and s_1^k to d_2^k be denoted by $p_a^{11}(k)$ and $p_a^{12}(k)$, respectively. The link-disjoint backup lightpaths from s_1^k to d_1^k and s_1^k to d_2^k be denoted by $p_b^{11}(k)$ and $p_b^{12}(k)$, respectively. Similarly, the primary lightpaths from s_2^k to d_1^k and s_2^k to d_2^k be denoted by $p_a^{21}(k)$ and $p_a^{22}(k)$, respectively. The link-disjoint backup lightpaths from s_2^k to d_1^k and s_2^k to d_2^k be denoted by $p_b^{21}(k)$ and $p_b^{22}(k)$, respectively. Let L_k be the set of all links used in the primary and backup lightpaths for the connection request k, where $L_k = p_a^{11}(k) \cup p_a^{12}(k) \cup p_a^{21}(k) \cup p_a^{22}(k) \cup p_b^{11}(k) \cup p_b^{12}(k) \cup p_b^{21}(k) \cup p_b^{22}(k)$.

If the core network is reliable, $p_a^{11}(k)$, $p_a^{12}(k)$, $p_a^{21}(k)$, and $p_a^{22}(k)$ can share links on their paths as shown in Fig. 2(a). However, even if $p_a^{11}(k)$, $p_a^{12}(k)$, $p_a^{21}(k)$, and $p_a^{22}(k)$ are disjoint, they cannot protect simultaneous (independent) failures in the source access network, the core network, and the destination access network, as shown in Fig. 2(b). If the source access node of s_1^k, one link in the path $p_a^{21}(k)$ and the destination access node of d_1^k are simultaneous down, data cannot be sent from source S_k to destination D^k. In order to provide dual-homing protected service, we need $p_b^{11}(k)$, $p_b^{12}(k)$, $p_b^{21}(k)$, and $p_b^{22}(k)$ to protect $p_a^{11}(k)$, $p_a^{12}(k)$, $p_a^{21}(k)$, and $p_a^{22}(k)$. We have the following observations:

- $p_a^{11}(k)$ and $p_b^{11}(k)$ must be disjoint.
- $p_a^{12}(k)$ and $p_b^{12}(k)$ must be disjoint.
- $p_a^{21}(k)$ and $p_b^{21}(k)$ must be disjoint.
- $p_a^{22}(k)$ and $p_b^{22}(k)$ must be disjoint.
- $p_a^{11}(k)$, $p_a^{12}(k)$, $p_a^{21}(k)$, and $p_a^{22}(k)$ can share links on their paths.
- $p_b^{11}(k)$, $p_b^{12}(k)$, $p_b^{21}(k)$, and $p_b^{22}(k)$ can share links on their paths.
- $p_a^{11}(k)$, $p_b^{12}(k)$, $p_b^{21}(k)$, and $p_b^{22}(k)$ can share links on their paths.
- $p_a^{12}(k)$, $p_b^{11}(k)$, $p_b^{21}(k)$, and $p_b^{22}(k)$ can share links on their paths.
- $p_a^{21}(k)$, $p_b^{11}(k)$, $p_b^{12}(k)$, and $p_b^{22}(k)$ can share links on their paths.
- $p_a^{22}(k)$, $p_b^{11}(k)$, $p_b^{12}(k)$, and $p_b^{21}(k)$ can share links on their paths.

Fig. 2(c) illustrates these observations. Without loss of generality, we assume that each connection request will use no more than one wavelength on any link.

In this paper, we study how to route the lightpaths $p_a^{11}(k), p_a^{12}(k), p_a^{21}(k), p_a^{22}(k), p_b^{11}(k), p_b^{12}(k), p_b^{21}(k)$, and $p_b^{22}(k)$ for all connection requests in R simultaneously, which is called *Static Dual-Homing Protection*.

We assume that full-wavelength conversion capability is available at each OXC in the core network and that the wavelength conversion cost is not significant. We only consider the wavelength cost. Therefore, our objective in static dual-homing protection is to find the set of all links, L_k for each connection request k in R, such that the total cost C is minimum, given by,

$$C = \sum_{k \in R} \sum_{e \in L_k} c(e). \quad (1)$$

We develop an integer linear programming (ILP) formulation for the static dual-homing protection problem. We have the following notation:

- $x_a^1(k,e)$: 1 if Path $p_a^{11}(k)$ uses Link e, 0 otherwise.
- $x_b^1(k,e)$: 1 if Path $p_b^{11}(k)$ uses Link e, 0 otherwise.
- $x_a^2(k,e)$: 1 if Path $p_a^{21}(k)$ uses Link e, 0 otherwise.
- $x_b^2(k,e)$: 1 if Path $p_b^{21}(k)$ uses Link e, 0 otherwise.
- $x_a^3(k,e)$: 1 if Path $p_a^{12}(k)$ uses Link e, 0 otherwise.
- $x_b^3(k,e)$: 1 if Path $p_b^{12}(k)$ uses Link e, 0 otherwise.
- $x_a^4(k,e)$: 1 if Path $p_a^{22}(k)$ uses Link e, 0 otherwise.
- $x_b^4(k,e)$: 1 if Path $p_b^{22}(k)$ uses Link e, 0 otherwise.

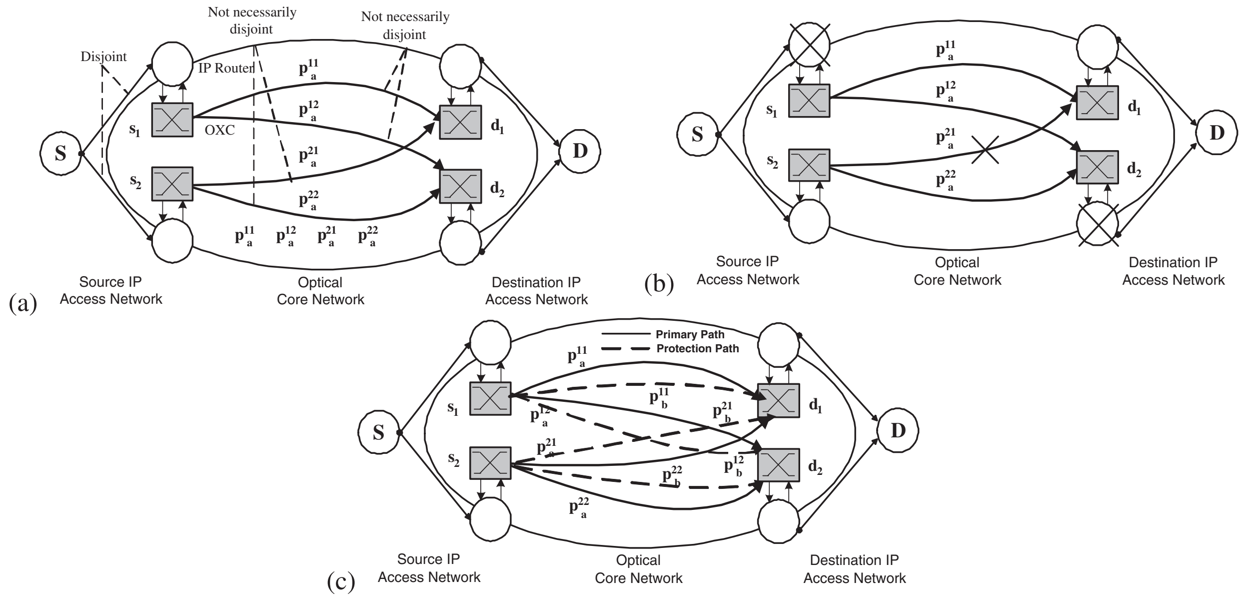


Fig. 2. Dual homing and protection architectures in IP-over-Optical networks.

- y_e^k: 1 if any path for connection request k uses Link e, 0 otherwise.
- y_e: total number of wavelengths used in Link e.
- $In(v)$: set of links that end at Node v.
- $Out(v)$: set of links that start from Node v.

The objective is to minimize:

$$\sum_{e \in E} y_e c(e) \tag{2}$$

subject to:

$$\sum_{e \in Out(s_1^k)} x_a^1(k,e) = 1 \quad \forall k \tag{3}$$

$$\sum_{e \in Out(s_1^k)} x_b^1(k,e) = 1 \quad \forall k \tag{4}$$

$$\sum_{e \in Out(s_2^k)} x_a^2(k,e) = 1 \quad \forall k \tag{5}$$

$$\sum_{e \in Out(s_2^k)} x_b^2(k,e) = 1 \quad \forall k \tag{6}$$

$$\sum_{e \in Out(s_1^k)} x_a^3(k,e) = 1 \quad \forall k \tag{7}$$

$$\sum_{e \in Out(s_1^k)} x_b^3(k,e) = 1 \quad \forall k \tag{8}$$

$$\sum_{e \in Out(s_2^k)} x_a^4(k,e) = 1 \quad \forall k \tag{9}$$

$$\sum_{e \in Out(s_2^k)} x_b^4(k,e) = 1 \quad \forall k \tag{10}$$

$$\sum_{e \in In(d_1^k)} x_a^1(k,e) = 1 \quad \forall k \tag{11}$$

$$\sum_{e \in In(d_1^k)} x_b^1(k,e) = 1 \quad \forall k \tag{12}$$

$$\sum_{e \in In(d_1^k)} x_a^2(k,e) = 1 \quad \forall k \tag{13}$$

$$\sum_{e \in In(d_1^k)} x_b^2(k,e) = 1 \quad \forall k \tag{14}$$

$$\sum_{e \in In(d_2^k)} x_a^3(k,e) = 1 \quad \forall k \tag{15}$$

$$\sum_{e \in In(d_2^k)} x_b^3(k,e) = 1 \quad \forall k \tag{16}$$

$$\sum_{e \in In(d_2^k)} x_a^4(k,e) = 1 \quad \forall k \tag{17}$$

$$\sum_{e \in In(d_2^k)} x_b^4(k,e) = 1 \quad \forall k \tag{18}$$

$$\sum_{e \in In(v)} x_a^1(k,e) = \sum_{e \in Out(v)} x_a^1(k,e) \quad \forall k, v, v \neq (s_1^k \mid\mid d_1^k) \tag{19}$$

$$\sum_{e \in In(v)} x_b^1(k,e) = \sum_{e \in Out(v)} x_b^1(k,e) \quad \forall k, v, v \neq (s_1^k \mid\mid d_1^k) \tag{20}$$

$$\sum_{e \in In(v)} x_a^2(k,e) = \sum_{e \in Out(v)} x_a^2(k,e) \quad \forall k, v, v \neq (s_2^k \mid\mid d_1^k) \tag{21}$$

$$\sum_{e \in In(v)} x_b^2(k,e) = \sum_{e \in Out(v)} x_b^2(k,e) \quad \forall k, v, v \neq (s_2^k \mid\mid d_1^k) \tag{22}$$

$$\sum_{e \in In(v)} x_a^3(k,e) = \sum_{e \in Out(v)} x_a^3(k,e) \quad \forall k, v, v \neq (s_1^k \mid\mid d_2^k) \tag{23}$$

$$\sum_{e \in In(v)} x_b^3(k,e) = \sum_{e \in Out(v)} x_b^3(k,e) \quad \forall k, v, v \neq (s_1^k \mid\mid d_2^k) \tag{24}$$

$$\sum_{e \in In(v)} x_a^4(k,e) = \sum_{e \in Out(v)} x_a^4(k,e) \quad \forall k, v, v \neq (s_2^k \mid\mid d_2^k) \tag{25}$$

$$\sum_{e \in In(v)} x_b^4(k,e) = \sum_{e \in Out(v)} x_b^4(k,e) \quad \forall k, v, v \neq (s_2^k \mid\mid d_2^k) \tag{26}$$

$$x_a^1(k,e) + x_b^1(k,e) \le 1 \quad \forall k,e \quad (27)$$
$$x_a^2(k,e) + x_b^2(k,e) \le 1 \quad \forall k,e \quad (28)$$
$$x_a^3(k,e) + x_b^3(k,e) \le 1 \quad \forall k,e \quad (29)$$
$$x_a^4(k,e) + x_b^4(k,e) \le 1 \quad \forall k,e \quad (30)$$
$$y_e^k \ge \frac{1}{8}(x_a^1(k,e) + x_b^1(k,e) + x_a^2(k,e) + x_b^2(k,e) + x_a^3(k,e) + x_b^3(k,e) + x_a^4(k,e) + x_b^4(k,e)) \quad \forall k,e \quad (31)$$
$$y_e = \sum_k y_e^k \quad \forall e \quad (32)$$
$$y_e \le W \quad \forall e \quad (33)$$

$$y_e^k \in \{0,1\} \quad \forall k,e \quad (34)$$
$$x_a^1(k,e) \in \{0,1\} \quad \forall k,e \quad (35)$$
$$x_b^1(k,e) \in \{0,1\} \quad \forall k,e \quad (36)$$
$$x_a^2(k,e) \in \{0,1\} \quad \forall k,e \quad (37)$$
$$x_b^2(k,e) \in \{0,1\} \quad \forall k,e \quad (38)$$
$$x_a^3(k,e) \in \{0,1\} \quad \forall k,e \quad (39)$$
$$x_b^3(k,e) \in \{0,1\} \quad \forall k,e \quad (40)$$
$$x_a^4(k,e) \in \{0,1\} \quad \forall k,e \quad (41)$$
$$x_b^4(k,e) \in \{0,1\} \quad \forall k,e \quad (42)$$

Constraints (3) - (26) are the network flow conservation constraints. Constraint (27) forces $p_a^{11}(k)$ and $p_b^{11}(k)$ to be disjoint, and constraint (28) forces $p_a^{21}(k)$ and $p_b^{21}(k)$ to be disjoint. Similarly, constraint (29) forces $p_a^{12}(k)$ and $p_b^{12}(k)$ to be disjoint, and constraint (30) forces $p_a^{22}(k)$ and $p_b^{22}(k)$ to be disjoint. Constraint (31) indicates that no more than one wavelength is reserved in any link e for a connection request r_k. Constraints (32) and (33) indicate the maximum connection requests a link can support. Constraints (34) and (42) indicate the integer constraint on the variables.

III. Heuristic Algorithms

We now propose several heuristics for static dual-homing protection. These heuristics can be classified into two categories: one category is based on a minimum cost network flow model and the other category is based on a minimum Steiner tree model. The minimum cost network flow model computes minimum-cost link-disjoint paths which satisfy the disjointness between the primary path and the backup path [21]. On the other hand, the minimum Steiner tree model considers the sharing among the primary paths and sharing among the backup paths.

These heuristic algorithms find the primary and backup paths for each connection in R one by one. Since we only consider one connection request in the heuristic algorithms, for simplicity, we will omit the index variable k from the notations in the previous sections. Instead, let s_1 and s_2 be the two source edge routers. Let d_1 and d_2 be the destination routers of the connection request, respectively.

The first heuristic is based on minimum cost network flows. The heuristic finds the optimal link-disjoint primary and backup lightpaths from each of the dual source edge routers to each of the dual destination edge routers. The approach to obtain the solution by this heuristic is illustrated in Fig. 3(a).

The second heuristic is also based on minimum cost network flows and is a generalization of the first heuristic in which we first select two nodes known as the *branching nodes*. From each of the source dual homes we compute two minimum-cost link-disjoint paths to one branching node, and from that branching node we compute two minimum cost link-disjoint paths to one of the destination routers. After that, from each of two source routers, we compute two minimum-cost link-disjoint paths to the other branching node, and from that branching node we compute two minimum cost link-disjoint paths to the other destination router. This process is repeated, selecting a pair of nodes as the branching nodes, and then choosing the minimum cost solution. The first heuristic is a special case of the second heuristic in which the two destination routers are chosen as the branching nodes. Fig. 3(b) illustrates the steps to obtain the solution by this heuristic.

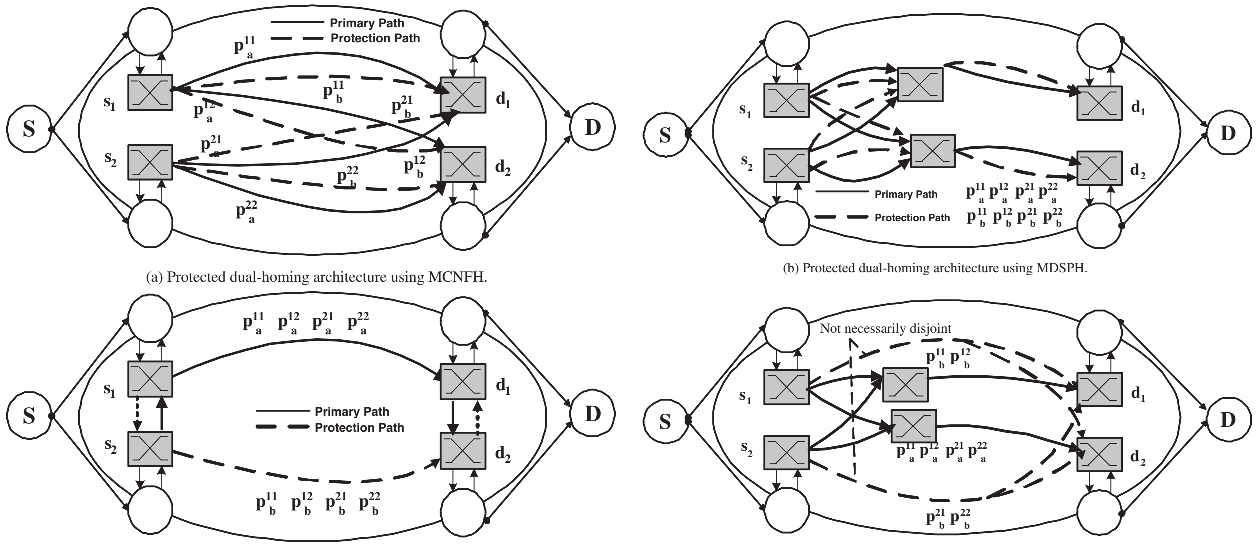
The third heuristic is also based on minimum cost network flow model and is motivated by the fact that the two source routers as well as the two destination routers are usually located close to each other. Here, we find the shortest link-disjoint paths from s_1 to d_1 and from s_2 to d_2, two minimum cost link-disjoint paths between the dual source routers, and two minimum cost link-disjoint paths between the dual destination routers. These six paths make up the primary and backup lightpaths. The solution obtained by this heuristic is illustrated in Fig. 3(c).

The last heuristic is based on the minimum Steiner tree. The heuristic finds a low-cost Steiner tree that connects the two source routers homes to the two destination routers. The primary paths are covered by the minimum Steiner tree. The heuristic then provides path protection from each source router to each destination router. This approach explicitly exploits the sharing of links between the primary lightpaths and is demonstrated in Fig. 3(d).

We now describe each of the heuristics in detail and compare their relative performance.

A. Minimum Cost Network Flow Heuristic (MCNFH)

The *minimum cost network flow heuristic* (MCNFH) first finds the minimum cost link-disjoint primary and backup lightpaths from the first source dual home to the first destination dual home, then changes the cost of the these links to zero (in order to encourage sharing) and



(a) Protected dual-homing architecture using MCNFH.

(b) Protected dual-homing architecture using MDSPH.

(c) Protected dual-homing architecture using MCSPH.

(d) Protected dual-homing architecture using MSTH.

Fig. 3. Dynamic dual-homing protection using different heuristics.

finds the minimum cost link-disjoint primary and backup lightpaths from the second source dual home to the first destination dual home. Then, finds the minimum cost link-disjoint primary and backup lightpaths from the first source dual home to the second destination dual home, then changes the cost of the these links to zero (in order to encourage sharing) and finds the minimum cost link-disjoint primary and backup lightpaths from the second source dual home to the second destination dual home.

We can use the minimum cost network flow (MCNF) algorithm to find the minimum-cost link-disjoint primary and backup lightpaths from one source home to one destination home. Initially, we set the capacity of link to be unity in order to force the primary and the backup lightpaths from s_1 to d_1 as well as from s_2 to d_1 to be disjoint. Note that the order in which the paths are computed has a bearing on the total cost. Hence, we first find the primary and backup lightpaths from one source dual home to one destination dual home, and then find the primary and backup lightpaths from the source dual homes to the other destination dual home. Then we exchange the order and repeat the same process. Finally, we select the solution having the minimum cost.

The detailed algorithm is given in Fig. 4. In Fig. 4, C gives the total cost for the primary and backup lightpaths from s_1 to d_1 and s_2 to d_1 as well as from s_1 to d_2 and s_2 to d_2, and S gives the links used for those lightpaths.

$C_1(s_1, d_1) = 0$; $C_1(s_2, d_1) = 0$; $C_1(s_1, d_2) = 0$;
$C_1(s_2, d_2) = 0$; $S_1 = \emptyset$;
Call MCNF(s_1, d_1) to find p_a^{11} and p_b^{11};
for ($e \in p_a^{11} \cup p_b^{11}$) {
    $C_1(s_1, d_1)$ += e; $S_1 = S_1 \cup \{e\}$;
    $BackupCost(e) = c(e)$; $c(e) = 0$;
}
Call MCNF(s_2, d_1) to find p_a^{21} and p_b^{21};
for ($e \in p_a^{21} \cup p_b^{21}$) {
    $C_1(s_2, d_1)$ += e; $BackupCost(e) = c(e)$;
}
Call MCNF(s_1, d_2) to find p_a^{12} and p_b^{12};
for ($e \in p_a^{12} \cup p_b^{12}$) {
    $C_1(s_1, d_2)$ += e;
    $BackupCost(e) = c(e)$; $c(e) = 0$;
}
Call MCNF(s_2, d_2) to find p_a^{22} and p_b^{22};
for ($e \in p_a^{22} \cup p_b^{22}$) {
    $C_1(s_2, d_2)$ += e;
$BackupCost(e) = c(e)$;
}
$C_1 = C_1(s_1, d_1) + C_1(s_2, d_1)$
$+C_1(s_1, d_2) + C_1(s_2, d_2)$;
$S_1 = S_1 \cup p_a^{21} \cup p_b^{21} \cup p_a^{12} \cup p_b^{12} \cup p_a^{22} \cup p_b^{22}$
Find C_2, C_3, and C_4 from S_2, S_3, and S_4
(solutions with different ordering of paths)
$C = MIN(C_1, C_2, C_3, C_4)$
$S = S_{MIN}$;

Fig. 4. Minimum Cost Network Flow Heuristic (MCNFH) description.

B. Minimal Disjoint Segment-Pair Heuristic (MDSPH)

The minimal disjoint segment-pair heuristic (MDSPH) is based on the observation that the two primary paths from s_1 to d_1 and from s_2 to d_1 are either disjoint or there is a branching node which connects the two source homes and the first destination home. As a matter of fact, if these two primary paths are disjoint, it can still be considered as if there is a branching node located at the first destination. Obviously, the position of the branching node will affect the total cost of the primary lightpaths and backup lightpaths. The same observation holds for the two primary paths from s_1 to d_2 and from s_2 to d_2. Therefore, there are two branching nodes that we need to consider about.

The MDSPH tries to find the right branching nodes such that the total wavelength cost used in both primary paths and backup paths is minimum.

$C = \infty$
for $(v_i \in V)$
for $(v_j \in V)$ {
  $C_{ij} = 0$;
  Call MCNF(s_1, v_i) to find link-disjoint p_a^1 and p_b^1;
  $L_1(v_i) = p_a^1 \cup p_b^1$; $S_i = L_1(v_i)$;
  for $(e \in L_1(v_i))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  Call MCNF(s_2, v_i) to find link-disjoint p_a^2 and p_b^2;
  $L_2(v_i) = p_a^2 \cup p_b^2$; $S_i = S_i \cup L_2(v_i)$;
  for $(e \in L_2(v_i))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  Call MCNF(v_i, d_1) to find link-disjoint p_a^3 and p_b^3;
  $L_3(v_i) = p_a^3 \cup p_b^3$; $S_i = S_i \cup L_3(v_i)$;
  for $(e \in L_3(v_i))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  Call MCNF(s_1, v_j) to find link-disjoint p_a^4 and p_b^4;
  $L_1(v_j) = p_a^4 \cup p_b^4$; $S_j = L_1(v_j)$;
  for $(e \in L_1(v_j))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  Call MCNF(s_2, v_j) to find link-disjoint p_a^5 and p_b^5;
  $L_2(v_j) = p_a^5 \cup p_b^5$; $S_j = S_j \cup L_2(v_j)$;
  for $(e \in L_2(v_j))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  Call MCNF(v_j, d_2) to find link-disjoint p_a^6 and p_b^6;
  $L_3(v_j) = p_a^6 \cup p_b^6$; $S_j = S_j \cup L_3(v_j)$;
  for $(e \in L_3(v_j))$ {
    C_{ij} += $c(e)$; $BackupCost(e) = c(e)$; $c(e) = 0$;
  }
  if $(C > C_{ij})$ {
    $C = C_{ij}$; $v_{b_1} = v_i; v_{b_2} = v_j$
  }
  for $(e \in S_i \cup S_j)$
  $c(e) = BackupCost(e)$;
}

Fig. 5. Minimal Disjoint Segment-Pair Heuristic (MDSPH) description.

MDSPH is described in Fig. 5. Here, C gives the total cost of the solution found by MDSPH, and v_{b_1} and v_{b_2} give the branch nodes. MDSPH always finds a solution if a feasible solution exists. The solution obtained is no worse than MCNFH, since MCNFH is a special case of MDSPH where the two destination routers serve as the branching nodes.

C. Minimum Cost Shortest Path Heuristic (MCSPH)

In the minimum cost shortest path heuristic (MCSPH), we obtain link-disjoint shortest paths from s_1 to d_1 and from s_2 to d_2,then compute two link-disjoint minimum cost paths between s_1 and s_2. We also obtain two link-disjoint minimum cost paths between d_1 and d_2. The details of MCSPH are given in Fig. 6. The solution

$C_1 = 0$; $C_2 = 0$;
Call Dijkstra(s_1, d_1) to find shortest path p_a^1;
for $(e \in p_a^1)$ {
    C_1 += $c(e)$; $c(e) = \infty$;
}
Call Dijkstra(s_2, d_2) to find shortest path p_a^2;
for $(e \in p_a^2)$ {
    C_2 += $c(e)$; $c(e) = \infty$;
}
Call Dijkstra(s_1, s_2) to find shortest path p_b^1;
for $(e \in p_b^1)$ {
    C_2 += $c(e)$; $c(e) = \infty$;
}
Call Dijkstra(s_2, s_1) to find shortest path p_b^2;
for $(e \in p_b^2)$ {
    C_1 += $c(e)$; $c(e) = \infty$;
}
Call Dijkstra(d_1, d_2) to find shortest path p_c^1;
for $(e \in p_c^1)$ {
    C_1 += $c(e)$; $c(e) = \infty$;
}
Call Dijkstra(d_2, d_1) to find shortest path p_c^2;
for $(e \in p_c^2)$ {
    C_2 += $c(e)$; $c(e) = \infty$;
}
$p_a^{11} = p_a^1$; $p_b^{11} = p_b^1 \cup p_a^2 \cup p_c^2$;
$p_a^{21} = p_a^2 \cup p_c^2$; $p_b^{21} = p_b^2 \cup p_a^1$;
$p_a^{12} = p_a^1 \cup p_c^1$; $p_b^{12} = p_b^1 \cup p_a^2$;
$p_a^{22} = p_a^2$; $p_b^{22} = p_b^2 \cup p_a^1 \cup p_c^1$;
Repeat by switching the order of finding
the shortest paths and select the least-cost path.

Fig. 6. Minimum Cost Shortest Path Heuristic (MCSPH) description.

obtained is composed of four minimum cost link-disjoint primary paths among the dual source homes and the dual destination homes, $p_a^{11}, p_a^{12}, p_a^{21}$ and p_a^{22}. The backup path from s_1 to d_1 is composed of the path from s_1 to s_2, the path from s_2 to d_2, and the path from d_2 to d_1. The backup path from s_1 to d_2 is composed of the path from s_1 to s_2 and the path from s_1 to d_2. The backup path from s_2 to d_1 is composed of the path from s_2 to s_1 and the path from s_1 to d_1. The backup path from s_2 to d_2 is composed of the path from s_2 to s_1, the path from s_1 to d_1, and the path from d_1 to d_2.

D. Minimum Steiner Tree Heuristic (MSTH)

The minimum Steiner tree heuristic uses the fact that a minimum Steiner tree is the best approach to connect a set of nodes with minimum cost. The idea behind the minimum Steiner tree heuristic (MSTH) is to find a minimum cost tree which is designated as the primary tree and then provides path protection to the dual homes.

Although the minimum Steiner tree problem is NP-hard in the general case, it is polynomial-time solvable when there are only four terminal nodes. We observe that a tree with only four terminal nodes will have at most two branching (or splitting) nodes. Once the branching nodes are determined, the minimum cost Steiner tree is obtained by finding the shortest paths from two source homes to those two branching nodes, and the shortest paths from each branching node to the two destination homes.

In order to find the optimal two branching nodes in a network with N nodes, we can consider each pair of $v_i, v_j \in V$ to be the branching points and then T_{ij}, which consists of the shortest paths from s_1 to v_i, from s_2 to v_i, from v_i to d_1, from s_1 to v_j, from s_2 to v_j, from v_j to d_2, resulting in N^2 different trees. The optimal minimum Steiner tree, T_{opt}, is given by the minimum cost tree of the N^2 different enumerated trees. Four primary lightpaths are provided in T_{opt}. Then a link-disjoint backup lightpath is constructed from each source home to each destination home. The description of MSTH is given in Fig. 7.

$C_{min} = \infty$; $C = 0$;
for ($v_i \in V$) {
  for ($v_j \in V$) {
    Call Dijkstra(s_1, v_i) to find shortest path X_1;
    for ($e \in X_1$) { C+=c(e); c(e)=0 }
    Call Dijkstra(s_2, v_i) to find shortest path X_2;
    for ($e \in X_2$) { C+=c(e); c(e)=0 }
    if ($v_i \neq v_j$) {
      Call Dijkstra(s_1, v_j) to find shortest path X_3;
      for ($e \in X_3$) { C+=c(e); c(e)=0 }
      Call Dijkstra(s_2, v_j) to find shortest path X_4;
      for ($e \in X_4$) { C+=c(e); c(e)=0 }
    }
    Call Dijkstra(v_i, d_1) to find shortest path X_5;
    for ($e \in X_5$) { C+=c(e); c(e)=0 }
    Call Dijkstra(v_j, d_2) to find shortest path X_6;
    for ($e \in X_6$) { C+=c(e); c(e)=0 }
    if ($C < C_{min}$) {
      $p_a^{11} = X_1 \cup X_5$; $p_a^{12} = X_3 \cup X_6$;
      $p_a^{21} = X_2 \cup X_5$; $p_a^{22} = X_4 \cup X_6$;
    }
  }
}
for ($e \in p_a^{11}$) $c(e) = \infty$;
Call Dijkstra(s_1, d_1) to find shortest path p_b^{11};
Reset certain links for sharing
for ($e \in p_a^{12}$) $c(e) = \infty$;
Call Dijkstra(s_1, d_2) to find shortest path p_b^{12};
Reset certain links for sharing
for ($e \in p_a^{21}$) $c(e) = \infty$;
Call Dijkstra(s_2, d_1) to find shortest path p_b^{21};
Reset certain links for sharing
for ($e \in p_a^{22}$) $c(e) = \infty$;
Call Dijkstra(s_2, d_2) to find shortest path p_b^{22};

Fig. 7. Minimum Steiner Tree Heuristic (MSTH) description.

In Table I, we compare the time complexities of the proposed dual-homing protection heuristics. We see that the MCNFH and MCSPH have a worst-case time complexity $O(N^2)$, the generalized MDSPH has a worst-case time complexity $O(N^4)$, and the MSTH has a worst-case time complexity $O(N^4)$.

TABLE I
TIME COMPLEXITY: DYNAMIC DUAL-HOMING PROTECTION HEURISTICS.

Algorithm	Time Complexity
MCNFH	O(N^2)
MDSPH	O(N^4)
MCSPH	O(N^2)
MSTH	O(N^4)

IV. SIMULATION RESULTS

In this section, we analyze the performance of proposed algorithms for dual-homing protection. We are interested in comparing the performance of MCNFH, MDSPH, MCSPH, and MSTH. We also compare our solutions for the integrated dual-homing protection with a baseline solution obtained by providing protection without being aware of the dual-homing architecture.

A simulation model is developed in order to analyze the performance of the proposed heuristics for the dual-homing protection problem. The important simulation parameters include the network size, N, the maximum outgoing degree at each node, D, the maximum number of wavelengths in each link, W, and the total connections, K. Given a group of parameters $< N, D, W, >$, we randomly generate a network with N nodes. The outgoing degree of each Node i, is uniformly distributed in $[1, 2, \ldots, D]$. The cost of each link is set to unity. We then randomly generate K connection requests and for each connection, we randomly select two source homes and two destination homes.

In the first experiment, we fix $N = 50, D = 10, W = 8$ and change K from 4, 8, 12, 16, 20, 24, 28 to 32 and the performance is given in Fig. 8. Figure 8 shows that the performance of MDSPH and MSTH is better than MCNFH and MCSPH. There is significant improvement in your integrated dual-homing protection compared with the baseline solution.

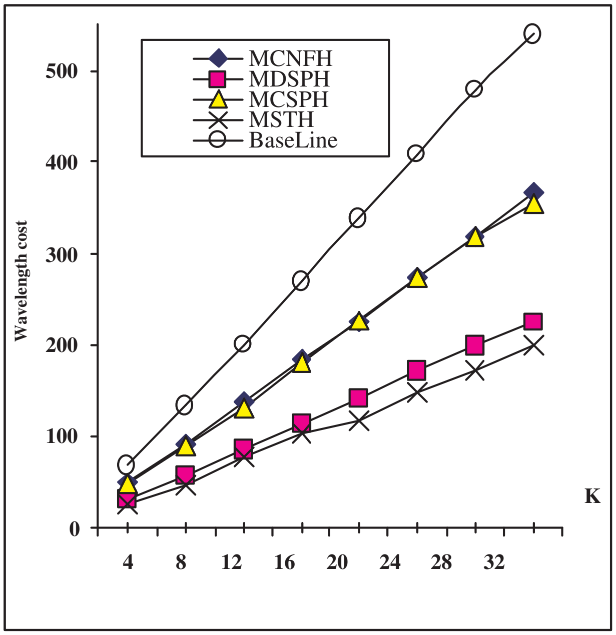


Fig. 8. Wavelength cost vs. K

In the second experiment, we fix $N = 50, K = 16, W = 8$ and change D from 4, 5, 6, 7, 8, 9 to 10. The performance is given in Fig. 9. Generally, when D increases, the total cost decreases with a denser network topology. Given the complexity of the four heuristic algorithms, MCNFH and MDSPH are good choice solutions. For a dense network (with larger D), MCNFH is the best choice which achieves a good balance between the running time, average cost, and the capability to find a feasible solution. For a sparse network (with smaller D), MCSPH is the best candidate to solve the dual-homing protection problem due to its faster running times and its ability to find low cost solutions.

V. Conclusion

We investigate the survivability issue in IP-over-WDM networks when a dual-homing architecture is provided in the access network. Our goal is to provide survivability for such an infrastructure subject to three independent failures, one failure from the source access network, one from the core network, and one failure from the destination access network. We developed an ILP model to formally define the problem. We also proposed four new heuristics, namely MCNFH, MDSPH, MCSPH, and MSTH to solve the dual homing protection problem. These heuristics can be classified into two categories:

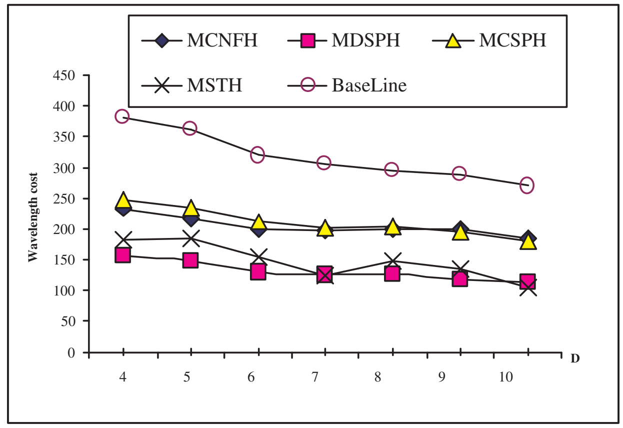


Fig. 9. Wavelength cost vs. D

those based on the minimum cost network flow model and those based on the minimum Steiner tree model. We observe that by following an integrated approach that considers the dual-homed IP-over-WDM architecture as compared to an independent solution at each layer (IP and WDM), we can significantly reduce the cost incurred to provide protection in the WDM core network. Areas of future work include introducing the concept of shared path protection into our integrated approach.

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