Lightpath Routing and Capacity Assignment for Survivable IP-over-WDM Networks

Invited Paper

Daniel Dao-Jun Kan
dankan@mit.edu

Aradhana Narula-Tam
arad@ll.mit.edu

Eytan Modiano
modiano@mit.edu

Abstract— **In IP-over-WDM networks the logical topology consists of a set of lightpaths that are routed on top of the physical fiber topology. Hence a single fiber cut can lead to multiple logical link failures. We study the impact of lightpath routing on network survivability and spare capacity requirements. We show that poor routings can lead to significant increase in spare capacity requirements and develop new metrics for assessing the survivability of different lightpath routings. Finally, we use these metrics to develop joint lightpath routing and capacity assignment algorithms that significantly reduce the spare capacity requirements of IP-over-WDM networks.**

I. Introduction

We consider the problem of providing protection and restoration for IP-over-WDM networks against fiber link failures. We assume a simplified IP-over-WDM network model as shown in Fig. 1. The physical topology consists of nodes with optical cross connects (OXCs) connected via fiber links. An OXC can switch the optical signal on a WDM channel from an input port to an output port without requiring the signal to undergo any optoelectronic conversion. The nodes in the logical topology correspond to the IP routers, and a link in this topology represents a direct optical connection between two IP router ports realized by a lightpath that has been established between the corresponding nodes. We often refer to the lightpath as the logical link, and the fiber link as the physical link. These lightpaths will carry IP traffic between the IP routers. Traffic demands at the IP layer may traverse multiple IP routers and lightpaths. In this paper, we consider the total traffic demand asserted by this IP traffic at the logical or lightpath layer. Hence the lightpath traffic demand is a sum of the IP traffic that traverses a particular lightpath.

The work of D. Kan was supported by DARPA Grant MDA972-02-1-0021. The work of A. Narula-Tam was supported by DARPA under Air Force Contract FA8721-05-C-0002. The work of E. Modiano was supported by NSF grant CNS-0830961 and by DTRA grant HDTRA1-07-1-0004. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

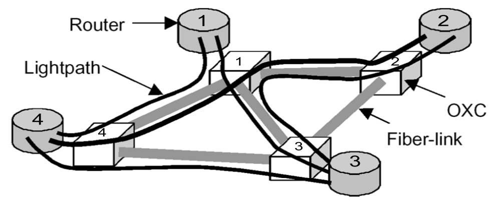


Fig. 1. An IP network overlaid on the WDM network

For an IP-over-WDM network, protection can be offered at the optical layer or the electronic layer. We focus on providing protection at the electronic layer because it is more capacity efficient and less costly to implement [1]. Protection at the electronic layer requires provisioning the network with sufficient spare capacity. After a physical link failure, IP routers can reroute the disrupted traffic on alternate paths, which must have enough spare capacity to support the additional traffic. Alternate paths can be dynamically found via an interior gateway protocol (IGP) or pre-established through multiprotocol label switching (MPLS).

We define *network survivability* for an IP-over-WDM network as the ability of the network to recover from any single physical link failure. Two criteria must be satisfied in order to ensure network survivability: 1) the source and destination of every traffic demand must remain connected after any physical link failure, and 2) the spare capacity in the network must be sufficient to support all of the disrupted traffic. The first criterion can be satisfied if the logical topology remains connected after any physical link failure. We call a routing *survivable*[1] if any physical link failure leaves the logical topology connected. The problem of finding such a routing of the logical links on the physical topology has been studied in [4]-[7], [2].

[1]We differentiate routing survivability from network survivability. The former refers to the connectivity of the logical topology after any physical link failure. The latter refers to the ability to restore network traffic.

However, the network must also have sufficient spare capacity to reroute the disrupted traffic.

Determining where to place spare capacity in the network and how much spare capacity must be allocated to guarantee the restoration of the network against single link failures is called the spare capacity allocation problem. A considerable amount of effort has been put into solving this problem for different networks such as SONET/SDH [10]-[12], ATM [8], [9], WDM [1], [3], and IP/MPLS [13]. However, these works do not consider the notion of a higher layer (i.e. logical topology) being embedded on a lower layer (i.e. physical topology). They also assume single link failures. In an IP-over-WDM network, a single physical link failure can result in the failure of multiple logical links, thus the routing of the logical links on the physical topology directly inherently affects the spare capacity requirement.

We consider protection at the IP layer. Hence a fraction of each logical link (lightpath) is assumed to carry working traffic, while the remainder of the logical link is presumed to be reserved for protection traffic in the case of a physical link failure. We would like to route the lightpaths on the physical layer topology in order to minimize the amount of spare capacity required. The main contribution of this paper is the solution to the joint problem of lightpath routing and spare capacity assignment. Instead of formulating the joint problem as one complete optimization problem, we break down the problem and establish important relationships between lightpath routing and spare capacity assignment. This approach not only makes the problem more tractable, but more importantly it gives a deeper understanding on the effects of lightpath routing on the spare capacity requirement in IP-over-WDM networks.

The rest of the paper is organized as follows. In Section II, we introduce two novel criteria, called the load factor and the spare factor, for measuring the quality of the lightpath routing. We show that the lightpath routing that maximizes the load factor or minimizes the spare factor requires significantly less capacity than the survivable lightpath routing approach of [6], which only considered network connectivity. In Section III, we develop a heuristic algorithm based on the two criteria for the joint problem of lightpath routing and capacity assignment. We compare capacity requirements under link restoration and end-to-end restoration. Finally, in Section IV, we present our conclusion.

A. Notations and Assumptions

We define some general notations and assumptions that are used throughout the rest of the paper.

Let (N_P, E_P) denote the physical topology, which consists of a set of nodes $N_P = \{1...|N_P|\}$ and a set of links E_P where link (i, j) is in E_P if a fiber link exists between node i and j. We assume a bidirectional physical topology, where if link (i, j) is in E_P so is link (j, i). Let $E'_P = \{(i, j) \in E_P \ : \ i > j\}$ denote the set of bidirectional physical links. We assume that a failure (fiber cut) of link (i, j) will also result in a failure of link (j, i). This assumption stems from the fact that the physical fiber carrying the link from i to j is typically bundled together with that from j to i. In some systems, the same fiber is used for communicating in both directions.

Let (N_L, E_L) denote the logical topology. The logical topology can be described by a set of nodes N_L and a set of links E_L, where N_L is a subset of N_P and link (s, t) is in E_L if both s and t are in N_L and there exists a logical link, or a lightpath, between them. We also assume a bidirectional logical topology. Given a logical topology, we want to route every logical link on the physical topology. Let $f_{ij}^{st} = 1$ if logical link (s, t) is routed on physical link (i, j), and 0 otherwise. We denote the routing of the logical topology by the assignment of values to the variables f_{ij}^{st} for all physical links (i, j) and logical links (s, t). Every logical link (s, t) is associated with a capacity denoted by C^{st}. The capacity of each logical link (s,t) is divided into working capacity and spare capacity denoted by β^{st} and μ^{st}, respectively.

II. Lightpath Routing

Lightpaths should be provisioned with sufficient spare capacity to protect against failures. The routing of the lightpaths on the physical topology can significantly affect the amount of capacity required for network survivability. In this section, we introduce two criteria, the load factor and the spare factor, for measuring the quality of the routing. We show that routing strategies based on these criteria can significantly reduce the capacity requirement for network survivability.

A. The Load Factor

In this section, we present a general strategy for routing the logical topology on the physical topology. This routing strategy is useful when the working capacity requirements of each lightpath is variable or unknown.

We associate a routing of the logical topology with a quantity between 0 and 1, denoted by α. Assume each link has capacity C then αC of each link is used for working traffic and $(1 - \alpha)C$ of each link is reserved for traffic disrupted due to link failures. Without loss of generality, we assume $C = 1$ because it is only a scaling factor. For a given routing of the logical topology, we define the load factor α to be the maximum achievable value that satisfies network survivability. The load factor directly gives us a measure of network redundancy. Consequently, we want to find a routing that maximizes the load factor.

We establish a necessary condition on the load factor and the corresponding routing using the maximum-flow minimum-cut theorem [16]. First, we define some new notations. A cut is a partition of the set of nodes N into two parts: S and $N-S$. Associated with each cut is a set of links, where each link has one node in S and the other node in $N-S$. We refer to this set of links as the cut-set associated with the cut $\langle S, N-S\rangle$, or simply $CS(S)$. Let $|CS(S)|$ equal the number of links in the cut-set.

Given a routing of the logical topology denoted by the assignment of values to the variables f_{ij}^{st}, the following lemma gives a necessary and sufficient condition on the load factor.

Lemma 1: A network is survivable if and only if for every cut-set $CS(S)$ of the logical topology and every physical link failure (i,j), the load factor satisfies the following inequality:

$$\sum_{(s,t)\in CS(S)} (f_{ij}^{st}+f_{ji}^{st})\alpha \le \sum_{(s,t)\in CS(S)} [1-(f_{ij}^{st}+f_{ji}^{st})](1-\alpha). \quad (1)$$

Proof:

We assumed a physical link failure corresponds to the failure of a bidirectional link. Therefore, $f_{ij}^{st}+f_{ji}^{st}=1$ implies that the logical link (s,t) will be broken if physical link (i,j) fails. Likewise, $f_{ij}^{st}+f_{ji}^{st}=0$ implies that the logical link (s,t) will remain intact. The above condition states that the amount of working capacity lost on the broken logical links in the cut-set due to a physical link failure must be less than or equal to the amount of spare capacity on the remaining logical links in the cut-set. This condition must hold for every cut-set of the logical topology and every single physical link failure. This follows directly from the maximum-flow minimum-cut theorem. ■

For a cut-set $CS(S)$, $\frac{|CS(S)|-\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})}{|CS(S)|}$ is the fraction of logical links within the cut-set that remain intact after physical link failure (i,j). For a given routing of the logical topology, we show that the load factor α is the minimum of such fractions over all cut-sets and all possible single physical link failures.

Theorem 1: Given the routing denoted by the set of variables f_{ij}^{st},

$$\alpha = \min_{\substack{S\subset N_L\\(i,j)\in E_P'}} \frac{|CS(S)|-\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})}{|CS(S)|}. \quad (2)$$

Proof: Rearranging (1) from Lemma 1 yields $\alpha \le \frac{|CS(S)|-\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})}{|CS(S)|}$. Since the load factor is defined to be the maximum value that satisfies the inequality for every cut-set and every physical link failure for the given routing, this condition is equivalent to (2). ■

Let $\{f_{ij}^{st}\}^*$ denote the routing that maximizes the load factor, and R denote the set of all possible routings. Using Theorem 1,

$$\{f_{ij}^{st}\}^* = \arg\min_{\{f_{ij}^{st}\}\in R} \max_{\substack{S\subset N_L\\(i,j)\in E_P'}} \frac{\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})}{|CS(S)|}. \quad (3)$$

Finding a routing that maximizes the load factor is equivalent to finding one that minimizes the maximum fraction of broken logical links in the cut-set. Intuitively, if the fraction of broken logical links in every cut-set is small, the logical topology remains well-connected after the physical link failure. This implies that even if the broken logical links had carried a large amount of working traffic, there exist enough diverse backup routes to reroute the disrupted traffic. Therefore, the load factor can also be interpreted as a quantity for measuring the disjointness of the corresponding routing. The larger the load factor, the more disjoint the routing is.

B. The Spare Factor

In this section, we investigate the lightpath routing and capacity allocation problem from a slightly different perspective. Here we assume that in addition to the logical topology, we are also given the working capacity β^{st} associated with each logical link, corresponding to the amount of working traffic that must be carried on each lightpath. The goal is to route the logical topology in a manner that reduces the total spare capacity required for network survivability. The new routing strategy tailors the routing for a given set of working capacity requirements unlike the routing strategy that maximizes the load factor, which essentially assumes the working capacity requirements on each lightpath are the same.

We begin by establishing a necessary and sufficient condition on the routing and spare capacity assignment to ensure network survivability.

Lemma 2: Given the working capacity of each logical link (s,t) is β^{st}, the routing of the logical topology and the corresponding spare capacity assignment μ^{st} must satisfy

$$\sum_{(s,t)\in CS(S)} (f_{ij}^{st}+f_{ji}^{st})\beta^{st} \le \sum_{(s,t)\in CS(S)} [1-(f_{ij}^{st}+f_{ji}^{st})]\mu^{st},$$
$$\forall S\subset N_L,\ (i,j)\in E_P'. \quad (4)$$

Proof: The proof is the same as Lemma 1, which follows directly from the maximum-flow minimum-cut theorem. ■

We now show how lightpath routing implicitly provides an upper bound on the total spare capacity requirement. For each cut-set $CS(S)$, the fraction of the working capacity lost over the total working capacity due to physical link failure (i,j) is $\frac{\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st}}{\sum_{(s,t)\in CS(S)}\beta^{st}}$. Given any routing, if this fraction is upper bounded by f for every cut-set and every physical link failure, the following theorem provides an upper bound on the total spare capacity required for network survivability. Let $S{=}\sum_{(s,t)\in E_L}\mu^{st}$ be the total spare capacity, and $W{=}\sum_{(s,t)\in E_L}\beta^{st}$ be the total working capacity.

Theorem 2: Given a quantity f, where $0 \le f < 1$, if the routing satisfies the following condition:

$$\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st} \le f \sum_{(s,t)\in CS(S)}\beta^{st}, \quad \forall S\subset N_L,\ (i,j)\in E'_P, \tag{5}$$

then the total spare capacity is bounded by

$$S \le \frac{f}{1-f}W. \tag{6}$$

Proof: We prove by construction that if (5) is satisfied, such a set of spare capacity assignments always exists by choosing $\mu^{st}{=}\frac{f}{1-f}\beta^{st}$. The spare capacity assignment trivially satisfies (6) because $S = \sum_{(s,t)\in E_L}\frac{f}{1-f}\beta^{st}{=}\frac{f}{1-f}W$. The spare capacity assignment also satisfies Lemma 2 since

$$\sum_{(s,t)\in CS(S)}[1-(f_{ij}^{st}+f_{ji}^{st})]\mu^{st}$$
$$=\frac{f}{1-f}\sum_{(s,t)\in CS(S)}\beta^{st}-(f_{ij}^{st}+f_{ji}^{st})\beta^{st}\ge\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st},$$

where the last inequality follows from (5) by substituting $f\sum_{(s,t)\in CS(S)}\beta^{st}$ with $\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st}$. ■
The theorem states that if the routing satisfies (5) for a given f, $\frac{f}{1-f}W$ is an upper bound on the total spare capacity required for network survivability.

We call the minimum value of f that satisfies (5) the *spare factor* associated with the corresponding routing. For a given routing, the spare factor is the maximum fraction of working capacity lost in any cut-set due to a physical link failure. A smaller spare factor f corresponds to a lower upper bound on the total spare capacity required for the corresponding routing. Thus the spare factor can be used as a criterion for routing the logical topology. Intuitively, to reduce the fraction of working capacity lost in any cut-set, logical links with large working capacity should be routed on disjoint physical links. This implies that the routing should evenly distribute traffic among physical links. Note that when $\beta^{st}{=}\beta$ for every logical link (s,t), finding a routing that minimizes the spare factor corresponds to finding a routing that maximizes the load factor. In this scenario, the minimum spare factor f^* is related to the maximum load factor α^* by $f^* = 1-\alpha^*$.

C. Lower Bound on Spare Capacity

We obtain a lower bound on the total spare capacity required for network survivability for a given physical topology and logical topology. The lower bound is a direct consequence of Lemma 2 obtained by considering only single node cuts. More precisely, we examine the spare capacity requirement in the cut-set $CS(\{k\})$ for each node k. Let L_k and P_k denote the logical and physical degrees of node k, respectively. We derive bounds for the two cases: $L_k > P_k$ and $L_k \le P_k$.

We first study the case of $L_k > P_k$. For ease of explanation, let $W_k{=}\sum_{(s,t)\in CS(\{k\})}\beta^{st}$ be the sum of working capacities on all logical links incident to node k. Similarly, let $S_k{=}\sum_{(s,t)\in CS(\{k\})}\mu^{st}$ be the sum of spare capacities on all logical links incident to node k. Note that independent of the routing, under one of the P_k possible physical link failure scenarios, at least $\frac{1}{P_k}(W_k + S_k)$ amount of capacity would be lost. Thus at most $\frac{P_k-1}{P_k}(W_k{+}S_k)$ amount of capacity remains to protect W_k amount of working capacity. Thus network survivability requires $\frac{P_k-1}{P_k}(W_k+S_k)\ge W_k$, or equivalently

$$S_k \ge \frac{W_k}{P_k-1}. \tag{7}$$

In the case of $L_k \le P_k$, each logical link incident to node k can be routed on a distinct physical link. Thus capacity is lost only if one of the L_k physical links fails. Using the same argument as before, we establish the lower bound for node k as

$$S_k \ge \frac{W_k}{L_k-1}. \tag{8}$$

Since (7) and (8) must hold for every node k in N_L, combining the two equations and summing over all nodes yields the following lower bound on total spare capacity

$$\sum_{k\in E_L}S_k = \sum_{(s,t)\in E_L}\mu^{st} \ge \sum_{k\in N_L}\frac{\sum_{(s,t)\in CS(\{k\})}\beta^{st}}{\min(P_k,L_k)-1}. \tag{9}$$

D. Mixed Integer Linear Program Formulation

Both routing strategies developed above, based on the load factor and on the spare factor, can be formulated as mixed integer linear programs (MILPs). We refer to the problem of finding the routing that maximizes the load factor as the LF problem, and the problem of finding the routing that minimizes the spare factor as the SF problem. The spare capacity requirements associated with these routings can then be determined using a linear program.

MILP-LF: The criteria for maximizing the load factor given in (3) directly translates to minimizing the following objective function:

$$\max_{\substack{S\subset N_L\\ (i,j)\in E'_P}} \frac{\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})}{|CS(S)|}. \qquad (10)$$

The objective function has the form $\max_{i=1,\dots,m} \mathbf{c_i'x}$. It is piecewise linear and convex rather than linear [16]. Problems with piecewise linear convex objective functions can be solved by solving an equivalent MILP problem. Note that $\max_{i=1,\dots,m} \mathbf{c_i'x}$ is equal to the smallest number f that satisfies $f \geq \mathbf{c_i'x}$ for all i. For this reason, the LF problem is equivalent to the following MILP problem:
$minimize \quad f$
Subject to:

1) Load factor constraints:

$$f|CS(S)|\geq \sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st}), \quad \forall S\subset N_L, \forall (i,j)\in E'_P$$

2) Connectivity constraints:

$$\sum_{j:\,(i,j)\in E_P} f_{ij}^{st} - \sum_{j:\,(j,i)\in E_P} f_{ji}^{st} = \begin{cases} 1, & \text{if s=i} \\ -1, & \text{if t=i} \\ 0, & \text{otherwise} \end{cases},$$
$$\forall i \in N_P, \forall (s,t) \in E_L.$$

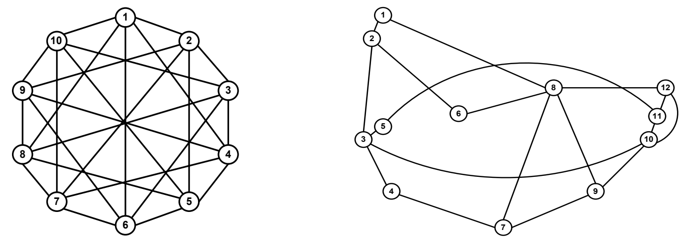
3) Integer flow constraints: $f_{ij}^{st} \in \{0,1\}$.

MILP-SF: The problem of finding a routing that minimizes the spare factor has the exact same structure as the LF problem. The only difference is that the load factor constraints are replaced with the following constraints:

1) Spare factor constraints:

$$f\sum_{(s,t)\in CS(S)} \beta^{st} \geq \sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st},\ \forall S\subset N_L, \forall (i,j)\in E'_P.$$

LP-SCA: Once the we obtain the routing by solving either MILP-LF or MILP-SF, we need to find the actual capacity allocations. Given the routing of the logical topology and a set of working capacity requirements, the problem of finding a corresponding spare capacity assignment that minimizes the total spare capacity can be formulated



(a) 10-node topology of degree 5

(b) 12-Node, 18-link Sprint OC-48 network

Fig. 2. Physical topologies used in simulations.

as the following LP:
$minimize \quad \sum_{(s,t)\in E_L} \mu^{st}$
Subject to:

1) Spare capacity constraints:

$$\sum_{(s,t)\in CS(S)}(f_{ij}^{st}+f_{ji}^{st})\beta^{st} \leq \sum_{(s,t)\in CS(S)}[1-(f_{ij}^{st}+f_{ji}^{st})]\mu^{st},$$
$$\forall S \subset N_L,\ (i,j) \in E'_P.$$

2) Nonnegativity constraints: $\mu^{st} \geq 0,\ \forall (s,t) \in E_L$.

Note that the spare capacity constraints are precisely the conditions given by Lemma 2.

E. Simulation Results

In our simulations, we used the 10-node topology of degree 5 and the Sprint OC-48 network shown in Fig. 2 as the underlying physical topologies. We define a topology of degree k to be a topology where every node has degree k. The 10-node topology of degree 5 is a dense and symmetric topology. On the other hand, the Sprint OC-48 network is a sparse and asymmetric topology. For each degree k ($k = 3, 4, 5, \dots$), we generated 50 random 10-node and 12-node logical topologies of degree k to be routed on the physical topologies. Associated with each random logical topology is a set of working capacity requirements, where the working capacity on every logical link is a uniformly distributed random variable between 1 and 5 inclusively.

Given a physical topology, a logical topology, and a set of working capacities, we compute the spare capacity requirement corresponding to the routing obtained under each of the following three routing strategies:

1) SR: Routing using the survivable routing algorithm presented in [6].
2) LF: Routing that maximizes the load factor.
3) SF: Routing that minimizes the spare factor.

We compare the LF and SF routing strategies with the survivable routing strategy [6], which does not take capacity requirement into account. For each routing, we solve

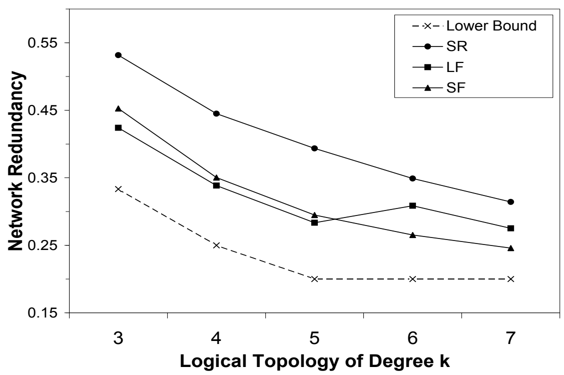


Fig. 3. Average network redundancy of embedding random 10-node logical topologies of degree k on the 10-node topology of degree 5.

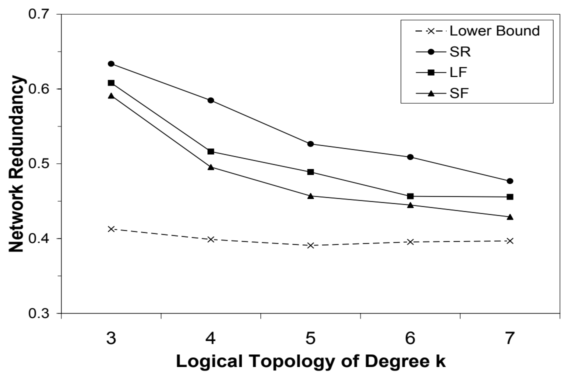


Fig. 4. Average network redundancy of embedding random 12-node logical topologies of degree k on the Sprint OC-48 network.

LP-SCA to determine the spare capacity requirement. For comparison convenience, we normalize the spare capacity requirement by expressing it in terms of network redundancy, which we define as the the ratio of total spare capacity to total capacity. We compare the spare capacity requirement under each routing strategy with the lower bound given by (9).

The average network redundancy required to embed 50 random logical topologies of degree k on the 10-node degree 5 physical topology is shown in Fig. 3. The figure shows that both LF and SF routing strategies consistently require less network redundancy than the SR routing strategy. This result confirms that the routing of the logical topology can significantly affect the spare capacity requirement. It is interesting to note that when the degree of the logical topology is high, the SF routing strategy, which attempts to distribute the traffic load along the physical links, outperforms the strategy based on the LF. A possible explanation is that when the degree of the logical topology is large, the routing strategy has more of an opportunity to distribute the traffic load along different links, leading to significant capacity savings.

Fig. 4 shows results of embedding random logical topologies on the Sprint OC-48 network. As expected, the LF and SF curves are significantly lower than the SR curve; however, the difference is less significant for logical topologies of low degree (e.g., 3). As the degree of the logical topology increases, the routing strategies based on LF and SF are able to take advantage of the diversity in the routes to significantly reduce the capacity requirements.

III. Joint Lightpath and Traffic Routing

So far, we have considered lightpath routing strategies that attempt to minimize the spare capacity requirements along each cut of the logical topology by routing the associated logical links along diverse physical paths. Next we consider end-to-end traffic demands, that must be supported by the logical network topology. In this case, it is necessary to route the traffic on the logical topology, route the logical topology on the physical topology, and assign working and spare capacities to each logical link so that the resulting network can withstand single fiber failures.

The joint optimization problem of lightpath routing, traffic routing, and capacity assignment is difficult to solve in general, because of the discrete nature of the lightpath routing problem. In fact, most previous work on survivability of IP-over-WDM networks assume that the routing of the lightpaths is given in advance. When the routing of the logical topology is given, the problem reduces to a linear program, which can be easily solved by the simplex method. Here, however, our goal is to optimize the routing of the lightpaths so as to reduce the spare capacity requirements. To that end, we will use a decomposition approach whereby we use the lightpath routing strategies of Section II to find highly survivable routings. We then solve the problem of traffic routing and capacity assignment on the logical topology using a Linear Programming Formulation.

A. *Traffic Routing and Capacity Assignment*

The LP formulation for the traffic routing and capacity assignment problem consists of three components: 1) routing the traffic on the logical topology, 2) rerouting disrupted traffic corresponding to each physical link failure, and 3) assigning working and spare capacities to each logical link. The objective is to minimize the total capacity required for network survivability for a given routing of the logical topology.

When a physical link fails, multiple logical links may fail. The backup routes used to reroute the disrupted traffic must only consist of links that are intact. Let G_{ij} denote the set of logical links that remain intact after physical link (i, j) fails, i.e. $G_{ij}=\{(s,t) \in E_L : f_{ij}^{st}+f_{ij}^{st}=0\}$.

We formulate the routing of the traffic demands as a multicommodity flow problem, where each traffic demand corresponds to a distinct commodity [16]. Let $T{=}\{(u,v):u,v{\in}N_L,u{\neq}v\}$ denote the set of all possible node pairs in the logical topology. Let λ^{uv} be the traffic demand for source-destination pair (u,v). We introduce flow variables λ_{st}^{uv} indicating the amount of traffic with source u and destination v that traverse logical link (s,t). We use the standard multicommodity flow formulation to express the following set of constraints on flow variables λ_{st}^{uv} associated with λ^{uv}:

$$\sum_{t:\,(s,t)\in E_L}\lambda_{st}^{uv}-\sum_{t:\,(t,s)\in E_L}\lambda_{ts}^{uv}=\begin{cases}\lambda^{uv}, & \text{if u=s}\\ -\lambda^{uv}, & \text{if v=s}\\ 0, & \text{otherwise}\end{cases},$$
$$\forall s\in N_L,\ (u,v)\in T. \qquad (11)$$

Given the routing of the traffic, the working traffic β^{st} on logical link (s,t) is the aggregation of flow from all the traffic demands traversing the link:

$$\beta^{st}=\sum_{(u,v)\in T}\lambda_{st}^{uv},\qquad \forall(s,t)\in E_L. \qquad (12)$$

Next we consider both link-based restoration and end-to-end restoration for spare capacity assignment. With link restoration, all of the traffic that traverses a failed logical link (s,t) is rerouted from node s to node t. In contrast, with end-to-end restoration interrupted traffic is rerouted along entirely new paths from the source node to the destination. Below we give the mathematical formulation for Link Restoration. Similar development for end-to-end restoration is omitted for brevity and can be found in [17].

Link Restoration: Let β_{ij}^{st} denote the amount of traffic that must be rerouted using backup routes that connect node s and node t after physical link (i,j) fails. Given the routing of the logical topology denoted by variables f_{ij}^{st}, $\beta_{ij}^{st}=(f_{ij}^{st}+f_{ji}^{st})\beta^{st}$. The disrupted traffic must be rerouted only on logical links in G_{ij}. We introduce flow variables $\gamma_{kl}^{st}(ij)$ indicating the amount of rerouted traffic with source s and destination t that traverses logical link (k,l) after physical link (i,j) fails. We use the multicommodity flow formulation to give the following set of constraints on variables $\gamma_{kl}^{st}(ij)$:

$$\sum_{l:\,(k,l)\in G_{ij}}\gamma_{kl}^{st}(ij)-\sum_{l:\,(l,k)\in G_{ij}}\gamma_{lk}^{st}(ij)=\begin{cases}\beta_{ij}^{st}, & \text{if s = k}\\ -\beta_{ij}^{st}, & \text{if t = k}\\ 0, & \text{otherwise}\end{cases},$$
$$\forall k\in N_L,\ (s,t)\in E_L,\ (i,j)\in E'_P. \qquad (13)$$

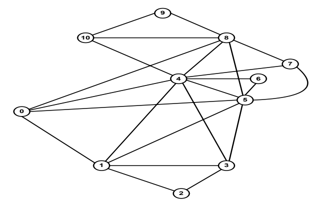


Fig. 5. The 11-node, 23-link New Jersey LATA network.

The spare capacity μ^{kl} on each logical link (k,l) must be sufficient to support the additional traffic under every physical link failure scenario:

$$\mu^{kl}\geq\sum_{(s,t)\in E_L}\gamma_{kl}^{st}(ij),\quad \forall(k,l)\in E_L,\ (i,j)\in E'_P. \quad (14)$$

Given the routing of the logical topology, the problem of finding the minimum capacity required for network survivability under link restoration is equivalent to the LP problem given by

$$minimize \sum_{(s,t)\in E_L}\beta^{st}{+}\mu^{st}$$

subject to (11)-(14) and nonnegativity constraints on variables λ_{st}^{uv} and $\gamma_{kl}^{st}(ij)$. If (11), (12) and variables λ_{st}^{uv} are removed, and variables β^{st} are given as a set of working capacity requirements, the result is an alternative flow-based formulation for the spare capacity assignment problem, which was formulated using the cut-set approach in Section II.

B. Decomposition Approach

In Section II, we developed two strategies for routing the logical topology on the physical topology. Maximizing the load factor (LF) provided a good general routing strategy without knowledge of capacity requirements for each lightpath. The spare factor (SF) algorithm uses knowledge of the traffic demand to further reduce the capacity requirements. Given the physical topology, the logical topology, and the traffic demands, we first use the LF routing strategy to obtain the initial routing and solve the corresponding capacity assignment problem to obtain the initial working capacity requirements. We then apply the SF routing strategy to further reduce the capacity requirements.

C. Simulation Results

We generated 50 random 11-node and 12-node logical topologies of degree k to embed on the New Jersey LATA network (see Fig. 5). We used random traffic demands, i.e. the traffic demand for every node pair is a uniformly

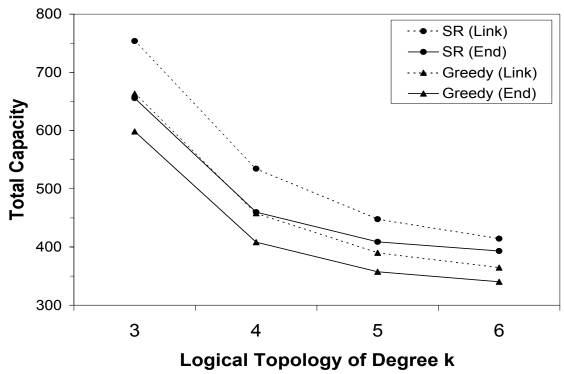


Fig. 6. Average total capacity of embedding random 11-node logical topologies of degree k on the New Jersey LATA network.

distributed random variable between 1 and 5 inclusively. We compared the capacity requirement returned by our greedy algorithm with that of the survivable routing algorithm (SR) [6].

Fig. 6 shows the average total capacity requirement for embedding random logical topologies on the New Jersey LATA network. The total capacity requirement is reduced by 10%-15% under both link restoration and end-to-restoration using the greedy heuristic when compared to the survivable routing algorithm. As expected, end-to-end restoration is more capacity efficient than link restoration. However, the efficiency decreases as the degree of the logical topology increases. Because the logical topology is more dense, less traffic is carried on each logical link. Furthermore, the spare capacity on each logical link can be shared by many more diverse backup routes that connect the end-nodes of the failed logical links.

IV. Conclusion

This paper considered the problem of joint lightpath routing and capacity assignment for survivable IP-over-WDM networks. In contrast to most previous works that assume that lightpath routing is determined in advance, we show that the lightpath routing has a significant impact on the spare capacity requirements. We developed new metrics for assessing the "survivability" of a lightpath routing and joint lightpath routing and capacity assignment algorithms that use these metrics to reduce spare capacity requirements.

This work is among the first to study the issue of survivability in layered network graphs. Future directions include the design of logical topologies and associated lightpath routings that are robust to physical link failures, and generalization to multi-failure scenarios.

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