The Effects of Multi-Layer Traffic on the Survivability of IP-over-WDM Networks

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***Abstract*—The survivability of backbone networks to failures is an on-going concern. This paper investigates survivability strategies for IP-over-WDM networks in a multi-layer framework where traffic originates at *each* layer. We present an optimization-based formulation of performing recovery mechanisms at the bottom layer for both layers of traffic in two cases: With capacity sharing between backup paths of the traffic in two layers and without. We then study and compare spare capacity requirements under multi-layer traffic ratios and the impact of network connectivity. Numerical results indicate that, in such a wavelength-based optical network, implementing survivability of all traffic at the bottom layer can be a viable solution with significant advantages.**

***Index Terms*—survivability, multilayer network design, spare capacity allocation**

I. INTRODUCTION

Revenue-generating IP and optical-switching WDM networks are moving toward an integrated high-speed backbone architecture with GMPLS as a common control plane. The ability of the network to survive link or node failures will be a required feature in future network infrastructure. However, multilayer planning is necessary to guarantee the survivability of traffic in a two-layer network.

Survivability of the traffic at both layers is essential as bandwidth at the lightpath level is becoming more in demand [1]; however, providing survivability to both IP flows and lightpaths is challenging. In most cases, these two-layer networks are under the same administrative ownership, but since the layers are formed by different technologies, interoperability between two layers of different technologies has become increasingly important.

Layers render a number of problems. First, failures at the bottom may tear down services at the top layer. This effect is called *failure propagation* and is at the forefront of problems in multilayer survivability. Survivable mapping, a map of a top-layer over a bottom-layer topology such that link failures at the bottom do not disconnect the top-layer topology, is a way to avoid such problem. Link mapping is almost always developed in anticipation of a single link failure [2]; however, ref. [3] has recently developed a mapping for multiple link failures.

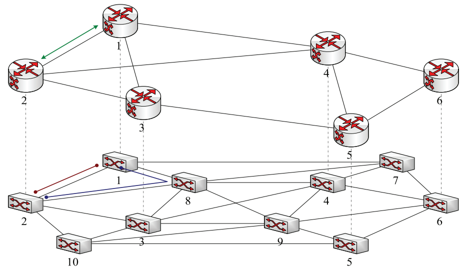

Fig. 1. A sample two-layer network

A second problem is, for a given mapping function, an IP top-layer path may require more or less bandwidth from the perspective of the top layer than that of the bottom, depending on which layer determines capacity allocation and routing assignment. For example, consider the top-layer path (1,2) in Fig. 1 when it is mapped to bottom-layer links (1,8) and (8,2). From a top-layer perspective, this IP path requires 2 capacity units at the bottom. However, from the bottom-layer perspective, it can be routed on a bottom-layer path (1,2), requiring only 1 capacity unit. Failure propagation also imposes difficulty in the network design phase as to deciding, for each IP top-layer path, which layer is responsible for failure recovery and under what conditions. This is because for an IP primary path, a backup path can be provided in either layer. Recovery mechanisms may also be redundant between two layers; however, this does not automatically imply that all of the mechanisms are used at both layers [4]. In addition, since capacity of a bottom link can simultaneously be shared by many top paths, allocating capacity among their corresponding backup paths in two layers becomes a concern; the services provided by the top-layer network must be survivable under failures at the bottom. Capacity allocation ensures sufficient link capacity for rerouting paths in the face of failures. Routing assignment guarantees that the end-to-end requirements are met, *e.g.,* availability, etc. In practice, dynamic and efficient multilayer routing algorithms [5] may be needed.

Similar to much of the work in this area, we jointly consider capacity allocation and routing assignment problems, in a core network, as a spare capacity allocation (SCA) problem. But, in addition, we examine several strategies for survivability in two-layer networks when traffic originates at *both* layers and grooming of the traffic, in each layer, is available at the edge. These strategies require traffic flows in both layers to be survivable under single link failure at the bottom. In particular,

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the following four survivability strategies are considered:

1) Strategy A: Backup paths are provided at the layer where traffic originates. Let BP_t^t be a set of top-layer backup paths to protect top-layer traffic, and BP_b^b be a set of bottom-layer backup paths to protect bottom-layer traffic. Sharing spare capacity between the two backup path sets is not allowed.
2) Strategy B: Similar to Strategy A but capacity between the two backup path sets BP_t^t and BP_b^b can be shared.
3) Strategy C: Backup paths of traffic at both layers are provided at the bottom layer. Let BP_b^t be a set of bottom-layer backup paths to protect top-layer traffic and BP_b^b as previously defined. Sharing capacity between the two backup path sets BP_b^t and BP_b^b is not allowed.
4) Strategy D: Similar to Strategy C but the capacity between the two backup path sets BP_b^t and BP_b^b can be shared.

For all strategies, spare capacity may be shared within a backup path set, *e.g.,* sharing capacity among backup paths in BP_b^b is allowed. Sharing is also allowed in BP_t^t as well as in BP_b^t.

This paper is organized in the following manner. In the next section, we provide background on multilayer survivability in two-layer networks. A mathematical formulation of the two survivability strategies at the bottom, C and D, is then presented in Section III. Performance evaluation of all strategies and numerical results are given in Section IV. Finally, our conclusions are summarized in Section V.

II. BACKGROUND

In the context of survivability in two-layer networks, several strategies have been proposed but they all share the same principle. Whether recovery can be initiated at either layer, both, or only at the bottom will be based on the originating traffic layer. When the traffic originates at the top, recovery can be performed at either layer or both, but when the traffic originates at the bottom, it can only be recovered at the bottom layer.

Survivability at the top provides backup paths to top-layer traffic at the top layer. Survivability strategy at this layer can be used to give multiple availability guarantees to traffic with priorities. This strategy can also resolve failures at both layers, *i.e.,* IP node, optical link, and WDM node failures. However, recovery time and rerouting states may be high due to the fact that each traffic flow needs to be recovered individually.

Survivability at the bottom provides backup paths to two-layer traffic at the bottom layer. Owning to fast failure detection and pre-reserved resources in WDM networks, recovery at this layer is usually faster [6]; however, it may not be able to provide survivability when failures happen at the top layer. In some cases, this strategy is not aware of the IP top-layer node failures unless there is an appropriate signalling coordination like GMPLS. In most cases, recovery at the optical bottom layer has to be performed on an aggregate basis, meaning that all IP flows that share the same failed optical link are rerouted to the same backup optical link. In the case of lightpath (re-)establishments in WDM networks, the situation is a little different: The IP flows that share that failed link can be rerouted to different lightpaths in optical links, giving more flexibility and better spare capacity utilization.

Survivability at both layers provides backup paths to top-layer traffic at both layers. By providing each top flow with two backup paths, one path at each layer, this strategy guarantees full recovery upon failures at any layer. In such a case, protection selectivity [7] or spare unprotected [8] refer to the strategy where sharing space capacity of the two backup paths is not allowed. When the capacity can be shared, it is known as common pool survivability [4], [8]. Alternatively, the backup path at the top layer can also be provided with a backup path at the bottom. In such a case, spare capacity is used twice, resulting in over-allocation of capacity.

Survivability can also be provided to traffic with multiple availability guarantees. In many cases, combinations of the above strategies are considered. For example, in traffic with two priority classes, survivability at the bottom and at the top can be provided to high-priority and low-priority traffic, respectively. Inter-level sharing between the two classes [9] can also be allowed. Integrated shared pool [10] considers 3 traffic classes: Gold, Silver, and Bronze. Survivability at the bottom is provided to Gold whereas survivability at the top is provided to Silver while there is no survivability guarantee for Bronze classes of traffic. In this strategy, sharing capacity among Gold backup paths, Silver backup paths, and Bronze primary paths is allowed. As there is no backup path for Bronze traffic, some capacity savings can be achieved by allocating spare capacity only to the two most important traffic classes. Idle protection capacity reuse [11] retains the same bottom-layer strategy for all 3 classes of traffic but chooses to explore possibilities in capacity-limited networks, *i.e.,* whether some paths can be preempted by others with higher priority upon failures and whether backup paths are preplanned or computed upon failures. Alternatively, a notion of shared risk link groups (SRLGs) can also be used to provide multiple guarantees to different traffic classes [12].

Implementing a survivability strategy in practice may depend on whether a two-layer network is under a single administrative management. Under the overlay model [13], neither layer network has a complete view of the other. In this case, from a global view, some care needs to be taken when allocating capacity or minimizing capacity costs because this can sometimes lead to different solutions from different perspectives of the top- and bottom-layer network providers; however, this situation is beyond the scope of this paper.

III. SURVIVABILITY OF TWO-LAYER TRAFFIC AT THE BOTTOM LAYER

In this section, we extend the SCA model in [14] to include survivability strategies when top-layer traffic is protected at the bottom layer. In this case, spare capacity due to the top BP_b^t and bottom BP_b^b layer traffic can either be unshared or shared. In addition, we consider a disjoint backup path from its primary path. The notation used is summarized in Table I.

TABLE I
NOTATION

Symbol	Definition
	from a {top, bottom}-layer perspective
$\mathcal{N}^{\{t,b\}}$	{Top, Bottom}-layer node set
$\mathcal{L}^{\{t,b\}}$	{Top, Bottom}-layer link set
$B^{\{t,b\}}$	{Top, Bottom}-layer incidence matrix w/ dimension $\lvert\mathcal{N}^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$
$F^{\{t,b\}}$	{Top, Bottom}-layer flow vector
$M^{\{t,b\}}$	Diagonal matrix of bandwidth of {top, bottom}-layer flow $f^{\{t,b\}}$ w/ dimension $\lvert F^{\{t,b\}}\rvert \times \lvert F^{\{t,b\}}\rvert$
$D^{\{t,b\}}$	{Top, Bottom}-layer flow-node incidence matrix w/ dimension $\lvert F^{\{t,b\}}\rvert \times \lvert\mathcal{N}^{\{t,b\}}\rvert$
$P^{\{t,b\}}$	Primary {top, bottom}-layer path matrix w/ dimension $\lvert F^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$
$Q^{\{t,b\}}$	Backup {top, bottom}-layer path matrix w/ dimension $\lvert F^{\{t,b\}}\rvert \times \lvert\mathcal{L}^{\{t,b\}}\rvert$
	from a bottom-layer perspective
$B^{t\to b}$	Top-layer incidence matrix w/ dimension $\lvert\mathcal{N}^{b}\rvert \times \lvert\mathcal{L}^{b}\rvert$
$M^{t\to b}$	Diagonal matrix of bandwidth of top-layer flow f^t w/ dimension $\lvert F^{t}\rvert \times \lvert F^{t}\rvert$
$D^{t\to b}$	Top-layer flow-node incidence matrix w/ dimension $\lvert F^{t}\rvert \times \lvert\mathcal{N}^{b}\rvert$
$P^{t\to b}$	Primary top-layer path matrix w/ dimension $\lvert F^{t}\rvert \times \lvert\mathcal{L}^{b}\rvert$
$Q^{t\to b}$	Backup top-layer path matrix w/ dimension $\lvert F^{t}\rvert \times \lvert\mathcal{L}^{b}\rvert$
$G^{t\to b}$	Top-layer spare capacity matrix w/ dimension $\lvert\mathcal{L}^{b}\rvert \times \lvert\mathcal{L}^{b}\rvert$
$S^{t\to b}$	Backup top-layer link capacity vector w/ dimension $\lvert\mathcal{L}^{b}\rvert \times 1$
G^{b}	Bottom-layer spare capacity matrix w/ dimension $\lvert\mathcal{L}^{b}\rvert \times \lvert\mathcal{L}^{b}\rvert$
S^{b}	Backup bottom-layer link capacity vector w/ dimension $\lvert\mathcal{L}^{b}\rvert \times 1$
H	Survivable mapping matrix
e	Column vector of ones

Our network of interest is defined as follows: Given a bottom-layer undirected network with node set $\mathcal{N}^b$, link set $\mathcal{L}^b$, and incidence matrix B^b [15], a top-layer undirected network with similar quantities in superscript t is constructed as follows: A node $n^t_k \in \mathcal{N}^t$, where $1 \leq k \leq |\mathcal{N}^t|$, exists only if its associative node $n^b_k \in \mathcal{N}^b$ at the bottom layer exists. That is, $\mathcal{N}^t \subseteq \mathcal{N}^b$. No more than one top-layer node is allowed to associate with a node at the bottom. Moreover, the presence of uncapacitated links at each layer is independent from one another.

Let H be a binary survivable mapping matrix, where $h_{ij} = 1$ if a top-layer link i is mapped onto a bottom-layer link j, and 0 otherwise. A survivable mapping matrix H can be derived from a necessary condition of a two-connected network, as presented in [2]. Now we have a topology construction including nodes, links, and link mapping. In the next two subsections, we will provide formulations of the SCA problem due to two-layer traffic.

A. Providing backup paths to top-layer traffic at the bottom

At the top layer, primary and backup paths of flows f^t, where $1 \leq f^t \leq |F^t|$ are represented by two $1\times|\mathcal{L}^t|$ binary row vectors $p^t_{f^t l^t}$ and $q^t_{f^t l^t}$, respectively. The l^t-th element in one of the vectors equals one if and only if the corresponding path uses link l^t. The path matrices [16] P^t and Q^t are formed by a collection of $p^t_{f^t l^t}$ and $q^t_{f^t l^t}$, respectively. The primary paths: P^t, can be obtained from Dijkstra's algorithm. Let $M^t = \mathbf{diag}(\{m^t_{f^t}\}_{|F^t|\times 1})$ be a matrix of top-layer integral flow bandwidth. The top-layer traffic flows are represented by a matrix D^t. An element $d^t_{f^t n^t}$ of the matrix D^t equals 1 if the flow f^t originates from node n^t and -1 if it terminates at node n^t. Flows having identical end points, if exist, are treated as a single flow with flow bandwidth from those flow bandwidths combined.

In order to provide backup paths to top-layer traffic at the bottom, we need to map top-layer information to the bottom. Because the incidence matrix is topology dependent, a top-layer incidence matrix, when mapped to the bottom, is equivalent to that of the bottom. This is shown in (1). In (2), bandwidth of the mapped top-layer flow still holds the same value, *i.e.,* $m^t_{f^t}$, as that of the top-layer flow as it depends on flows only. Since a top-layer network may not have the same number of nodes as the bottom, the flow-node incidence matrix in (3) is mapped to the bottom layer by padding columns of zeros as necessary to D^t. In (4), the link-mapping information in H is used to derive top-layer primary paths P^t from the perspective of the bottom layer, as $P^{t\to b}$. The $\odot$ symbol is a matrix multiplication operator, realizing the inclusive OR and AND operation, *e.g.,* 1+1=1. Using this operator, the logical relations among flows and links in an undirected network can be simplified into one matrix operation. Since binary flows are considered, we do not include a single-path routing constraint in our ILP formulation as it would be redundant.

A mapping function $f : t \to b$ can be described for each top-layer matrix as:

$$B^{t\to b} = B^b \tag{1}$$

$$M^{t\to b} = M^t \tag{2}$$

$$D^{t\to b} = [D^t|0] \tag{3}$$

$$P^{t\to b} = P^t \odot H \tag{4}$$

Using the notation and definitions given previously, the SCA problem of the top-layer traffic can be formulated as:

$$Q^{t\to b} \odot {B^{t\to b}}^T = D^{t\to b} \tag{5}$$

$$P^{t\to b} + Q^{t\to b} \preceq 1 \tag{6}$$

$$G^{t\to b} = {Q^{t\to b}}^T M^{t\to b} P^{t\to b} \tag{7}$$

$$S^{t\to b} \in \mathbb{Z}_+^{|\mathcal{L}^b|} \tag{8}$$

$$Q^{t\to b} : \text{binary matrix} \tag{9}$$

Constraints (5) and (6) guarantee that a backup path matrix $Q^{t\to b}$ is feasible via flow conservation constraints and disjoint from the primary paths. A matrix $Q^{t\to b}$ has the same dimension as $P^{t\to b}$, which is $|F^t| \times |\mathcal{L}^b|$. Constraint (7) determines the amount of spare capacity units needed in order to protect mapped top-layer primary paths which fail as the result of a single link failure at the bottom layer. This information is given in $G^{t\to b}$, which is a $(|\mathcal{L}^b|, |\mathcal{L}^b|)$ matrix. An element $g_{ij}^{t\to b}$ defines the spare capacity needed by bottom link i to reroute failed paths in the face of failure at bottom link j. Equation (8) defines integer variables, where $\mathbb{Z}_+^{|\mathcal{L}^b|}$ is the set of nonnegative integral $|\mathcal{L}^b|$-dimensional vectors; equation (9) defines a (0,1)-matrix variable, which will be explained further in the next section.

B. Providing backup paths to bottom-layer traffic at the bottom

Since providing backup paths to bottom-layer traffic at the bottom layer requires no mapping, we now have all necessary information to find the backup paths of traffic in both layers. It is equivalent to finding a set of disjoint primary-backup path pairs in single-layer networks. A mathematical formulation for survivability of two-layer traffic at the bottom layer can be written as:

$$Q^b \odot {B^b}^T = D^b \tag{10}$$

$$P^b + Q^b \preceq 1 \tag{11}$$

$$G^b = {Q^b}^T M^b P^b \tag{12}$$

$$S^b \in \mathbb{Z}_+^{|\mathcal{L}^b|} \tag{13}$$

$$Q^b : \text{binary matrix} \tag{14}$$

Similar to backup paths of top-layer traffic, a constraint set (10)-(14) defines backup paths $Q^b = \{q^b\}_{|F^b|\times|\mathcal{L}^b|}$ and the spare capacity $G^b = \{g^b\}_{|\mathcal{L}^b|\times|\mathcal{L}^b|}$ required to protect primary paths P^b of the bottom-layer traffic. As in Section III-A, the primary paths P^b can be obtained from Dijkstra's algorithm.

The objectives of the two strategies C and D are defined as follows: Strategy C has an objective to minimize the spare capacity requirements of the two-layer traffic independently, and so can be described as:

$$\min\, ({S^{t\to b}}^T + {S^b}^T)e, \tag{15}$$

where $S^{t\to b} = \text{row-max } G^{t\to b}$, $S^b = \text{row-max } G^b$, and e is a column vector of ones. The row-max (x) operation determines the maximum element in each row of the matrix x. This min-max optimization of spare capacity requirements ensures the minimum capacity that must be allocated for each bottom-layer link under single link failure at any other links.

The objective function of Strategy D is expressed as:

$$\min\, ({S^{t\to b,b}}^T)e, \tag{16}$$

where $S^{t\to b,b} = \text{row-max } (G^{t\to b} + G^b)$. This strategy merges the two spare capacity matrices and jointly consider them, allowing their spare capacity to be exchanged. The two survivability strategies at the bottom: C and D, and two strategies where traffic originates: A and B, from [14, Section III.B(B) and Section III.D] construct a basis for our study in this paper.

IV. NUMERICAL RESULTS

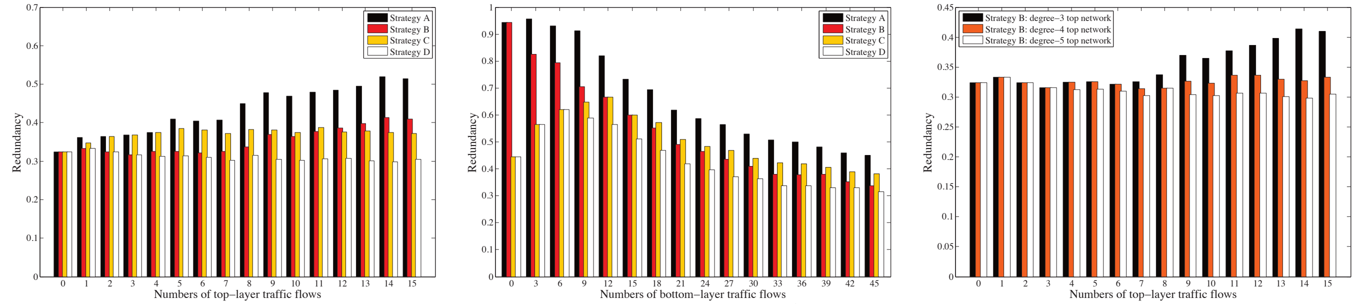
In this section, we study the effects of the survivability strategies on spare capacity requirements of multilayer traffic in two-layer networks. First, we look at the impact of traffic ratios between top- and bottom-layer in fixed network topologies as well as the impact of capacity sharing between the two-layer traffic. Then, we look at the impact of top-layer network connectivity in terms of average node degrees. We use AMPL/CPLEX 9.1 on a Sun Fire V240, 2x1.2GHz UltraSPARC IIIi, 2GB to solve our models and the results are based on a 0% integrality gap, meaning that they are optimal.

A two-layer network topology with a number of network scenarios is considered to determine the effects. The considered two-layer topology is Fig. 1 where the top has 6 nodes, 9 links and the bottom has 10 nodes, 22 links. Primary paths in both layers, when needed, are precomputed and unchanged over the course of simulations. A primary path is manually adjusted if the corresponding backup path cannot possibly be obtained, called a trap path. This is a counterexample to the existence of two disjoint paths in two-connected networks, when there are no parallel links. We are also aware that joint optimization of primary and backup paths often leads to better capacity utilization [17]; but since we want to focus on the spare capacity requirements of the survivability strategies, we let the primary paths be fixed. In addition, a number of wavelengths and wavelength converters are assumed to be available and unit-capacity flows are assumed.

A. Impacts of Traffic Ratios

In this section, the impacts of traffic ratios are discussed for the two possible settings: When the number of bottom-layer flows is fixed while varying the number of top-layer flows, and vice versa. With varying number of flows, f flows are chosen from the first f-th lexicographical element of the combinations of two elements out of the node set, *e.g.,* for 8 top-layer flows in Fig. 1, the considered flows are $(\{1,2\},\{1,3\},\{1,4\},\{1,5\},\{1,6\},\{2,3\},\{2,4\},\{2,5\})$. Spare capacity requirements are measured in terms of redundancy, or resource overbuild, which is defined as a capacity ratio of backup paths to primary paths.

1) varying top-layer flows: Over a fixed 45-flow bottom-layer network, Fig. 2(a) shows by varying a number of top-layer flows that Strategy A and Strategy D perform worst and best, respectively. The reasoning can be given as follows: Let us put aside bottom-layer traffic to consider top-layer traffic only. There are two survivability strategies for the top-layer traffic: Providing backup paths at the top layer and at the bottom. We claim that the first strategy never requires fewer spare capacity units than the latter. The reasons are as follows: First, a survivable matrix limits the number of feasible backup paths of top-layer traffic at the bottom. This is because the matrix ties a top-layer link to bottom-layer links, and this link mapping is not allowed to change. Second, spare capacity is provided by the bottom layer; regardless of where backup paths are computed, their capacity requirements are constrained by bottom-layer topology. This is also true even if the survivable matrix can be changed because constraints will be at the bottom-layer instead. In other words, if the number of top-layer links are significantly fewer than that of the bottom then the backup paths are limited by the top topology. But when the



(a) Top-layer flows vs. redundancy ($|F^b| = 45$)

(b) Bottom-layer flows vs. redundancy ($|F^t| = 8$)

(c) Redundancy of networks with top-layer connectivities ($|F^b| = 45$)

Fig. 2. Graphical results of Table II

number of top-layer links are significantly more than that of the bottom, a bottom topology itself limits improvements on capacity sharing by its own topology. An example when these two strategies are equivalent is when the two-layer topologies are identical and a survivable mapping is link-to-link. Now let us put bottom-layer traffic back into consideration. We have shown that, for top-layer traffic, bottom-layer backup paths require no more capacity than the top-layer counterpart. This is also true when there is bottom-layer traffic and sharing spare capacity between BP_b^b and BP_t^t or BP_b^t is not allowed. Since capacity sharing usually reduces spare capacity requirements, Strategy D always outperforms or at least performs as well as Strategy A. This analysis supports other topologies as well.

The other two strategies, however, are competing. When a top-layer network has few traffic flows, Strategy B outperforms Strategy C. This is because these few flows may well be able to share capacity with the bottom flows. But when there are more flows at the top layer, the situation is reversed.

Consider a scenario of 1 primary top-layer flow and 45 primary bottom-layer flows in Fig. 2(a). In this scenario, the bottom flows require 23 spare capacity units. Because of capacity sharing, Strategy B requires only 1 more capacity unit to provide a backup path to the top-layer flow. The total spare capacity required is now 24 units. However, in Strategy C, when sharing is not allowed, the backup path requires 2 capacity units. The spare capacity requirement of bottom-layer flows is never changed in Strategy C regardless of the number of top-layer flows because they do not allow capacity sharing with the top flows. In this scenario, primary paths require 1 and 71 capacity units for top- and bottom-layer flows, respectively.

When there are more flows, *i.e.,* more than 12 flows, in the top network, a higher number of flows in both layers are subject to failures. In this scenario, Strategy C reduces spare capacity requirements by giving more rerouting choices to the top flows. These choices offer an advantage over Strategy B. A similar trend is also observed for different numbers of top-layer flows, when bottom-layer flows are fixed, in Table II.

2) varying bottom-layer flows: In this section, we continue to evaluate Strategy B and C, but instead, the number of top-layer flows is fixed, and we vary the number of flows at the bottom layer.

Consider a scenario of 8 top-layer flows when the number of bottom flows ranges from 0 to 45, in multiples of 3. Unlike the above setting, this time Strategy C requires fewer capacity units than Strategy B when the number of bottom-layer flows is small. Fig. 2(b) shows that Strategy B starts to outperform Strategy C when there are 15 flows in the bottom-layer network. These results conform with our previous discussions in Section IV-A1 in terms of traffic ratios.

Observations in this section and Section IV-A1 suggest that there should be a characteristic of the competing two survivability strategies which could enable us to determine which strategy to implement to ensure better capacity utilization according to each network scenario. Due to space constraints, we decide to omit the discussion on the operating characteristics of the two survivability strategies.

B. Impacts of Network Connectivity

In this study, capacity requirements of top-layer networks with varying node degrees, 3, 4, and 5, over a bottom-layer network are compared. Networks in a family are related by link removals from a master network, while keeping nodes and demand flows fixed. The use of network families in simulations can resemble the results from many random networks while requiring much less simulation time. A more thorough analysis on the use of network families is provided in [18].

For a degree-3 top-layer network, we use the network shown in Fig. 1. A degree-4 top network can be accomplished by adding links $(1, 5), (2, 6)$, and $(3, 6)$ to the degree-3 network. A degree-5 top-layer network is set through its full mesh, *i.e.,* adding links $(1, 6), (2, 5)$, and $(3, 4)$ to the degree-4 network.

Since top-layer topologies have effect on the spare capacity requirements of neither Strategy C nor D, we focus only on Strategy A and B. Fig. 2(c) shows that reduction of spare capacity comes at an expense of a higher number of top-layer link installments in which a significant difference in capacity savings is observed when the number of top-layer flows is high. At 15 flows, which are the maximum number of distinct flows at the top, we observe a capacity saving of 9 units from a degree-3 to degree-5 network, compared to 2 when there are 8 flows at the top. One possible explanation is that an adding link can help reduce the capacity requirements by giving more routing choices to the backup paths. This link has little effect when there are few flows in the network, *i.e.,* 1-3 flows.

TABLE II
REDUNDANCY PERCENTAGE OF OPTIMAL SPARE CAPACITY†

Numbers of bottom-layer traffic flows	Numbers of top-layer traffic flows							
	0	1	2	3	4	5	6	7
0	—	300,300,100,100	133,133,67,67	100,100,60,60	78,78,67,67	92,92,50,50	85,85,46,46	80,80,47,47
3	100,100,100,100	133,100,100,100	113,88,88,88	100,80,80,80	86,79,79,79	94,76,65,65	89,72,61,61	85,70,60,60
6	91,91,91,91	108,100,92,100	100,86,86,86	94,88,81,81	85,75,80,70	91,83,70,70	88,79,67,67	85,77,65,62
9	88,88,88,88	100,88,88,88	95,84,84,84	90,81,81,76	84,76,80,72	89,75,71,68	86,72,69,66	84,71,68,65
12	71,71,71,71	82,73,77,73	79,71,79,71	77,65,77,65	73,67,73,63	79,67,73,61	76,65,71,62	75,92,67,58
15	59,59,59,59	68,61,64,61	67,60,67,60	66,56,66,56	64,58,64,56	69,59,64,54	68,58,63,53	67,57,60,52
18	55,55,55,55	63,59,59,59	62,56,62,56	61,56,61,53	60,55,60,53	65,53,60,51	64,52,59,50	63,52,57,48
21	46,46,46,46	53,50,50,50	53,48,53,48	52,48,52,45	52,48,52,52	57,47,53,45	56,46,52,44	56,46,50,42
24	43,43,43,43	49,46,46,46	49,44,49,44	49,44,49,42	49,47,49,45	54,44,50,42	53,43,49,42	53,44,47,40
27	41,41,41,41	47,44,44,42	47,43,47,43	47,41,47,41	47,43,47,42	52,41,48,39	51,40,47,39	51,41,46,37
30	38,38,38,38	43,41,41,39	43,39,43,39	43,38,43,38	44,40,44,39	48,40,45,38	48,39,44,38	48,40,43,37
33	36,36,36,36	41,37,39,37	41,36,41,36	41,34,41,34	42,37,42,35	46,37,43,35	45,36,42,35	46,37,41,34
36	36,36,36,36	40,37,39,37	41,36,41,36	41,34,41,34	42,37,42,35	46,37,43,35	45,36,42,35	45,37,41,34
39	34,34,34,34	39,35,37,35	39,34,39,34	39,33,39,33	40,36,40,34	44,36,41,34	43,35,41,34	43,36,39,33
42	33,33,33,33	37,34,35,34	37,33,37,33	38,33,38,33	38,34,38,33	42,34,39,33	41,34,39,33	41,34,38,32
45	32,32,32,32	36,33,35,33	36,32,36,32	37,32,37,32	38,33,38,31	41,33,39,31	40,32,38,31	41,33,37,30

Numbers of bottom-layer traffic flows	Numbers of top-layer traffic flows							
	8	9	10	11	12	13	14	15
0	94,94,44,44	100,100,48,48	88,88,40,40	89,89,41,41	87,87,37,37	88,88,38,38	94,94,36,36	91,91,35,35
3	96,83,57,57	100,88,58,50	90,80,50,47	91,81,50,50	89,77,46,49	89,76,46,46	95,82,45,45	92,79,44,44
6	59,79,62,62	97,84,63,59	89,78,56,56	89,76,55,55	88,76,51,54	88,77,51,51	93,80,50,50	91,78,49,49
9	91,71,65,59	95,76,65,54	88,71,59,51	88,70,58,51	87,67,54,50	88,69,54,48	92,71,53,47	90,70,52,46
12	82,67,67,56	86,69,64,52	80,65,61,48	81,67,63,50	80,67,59,49	81,66,58,47	85,69,57,46	84,67,56,45
15	73,60,60,51	77,63,58,48	73,60,56,44	74,61,57,46	74,63,54,46	75,63,54,44	78,65,53,43	77,64,52,43
18	69,55,57,47	73,58,56,44	70,55,54,43	71,57,55,43	70,59,52,43	71,59,52,41	75,61,52,41	74,60,51,40
21	62,49,51,42	66,52,50,40	63,50,48,39	64,52,50,41	64,54,48,39	65,54,48,38	69,56,47,37	68,55,46,37
24	59,47,48,40	62,49,48,38	60,48,46,37	61,49,48,39	61,51,46,39	63,51,46,38	66,53,45,37	65,53,45,36
27	56,44,47,37	60,46,46,35	58,45,45,35	59,46,46,37	59,49,45,36	61,49,45,36	64,51,44,35	63,50,44,35
30	53,41,44,36	57,43,43,35	55,42,42,34	56,44,44,35	56,46,42,35	58,46,43,34	60,48,42,33	60,48,41,33
33	51,38,42,34	54,41,42,32	53,40,41,32	54,41,43,33	54,43,41,33	55,44,41,32	58,45,41,31	57,45,40,32
36	50,38,42,34	53,42,42,32	52,41,41,32	53,42,42,34	53,43,41,34	55,44,41,33	57,46,40,33	57,46,40,32
39	48,38,41,33	51,41,40,33	50,40,40,33	51,41,41,33	52,43,40,34	53,44,40,33	55,46,39,33	55,45,39,33
42	46,35,39,33	49,39,36,32	48,38,38,32	49,39,39,32	49,40,38,32	51,41,38,31	53,43,38,31	52,43,38,32
45	45,34,38,31	48,37,38,30	47,36,38,30	48,38,39,31	49,38,38,31	50,40,38,30	52,41,38,30	51,41,37,30

†format: Strategies A, B, C, D

V. CONCLUSIONS

This paper examines the four possible survivability strategies in two-layer networks, where traffic presents at both layers. An optimization-based formulation is proposed to investigate the spare capacity requirements under various traffic ratios and network connectivities in the role of lightpath routing.

Numerical results show that the survivability of two-layer traffic at the bottom, when sharing spare capacity among all backup paths is allowed, performs best. However, two of the studied strategies are competing. Moreover, networks with higher average node degree can provide more capacity savings, but this comes at the expense of link installments. Our analysis and results provide important guidelines for the design of survivability strategies in networks and for understanding their tradeoffs. Future work may include differentiated survivability.

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