Logical Topology Survivability in IP-over-WDM Networks: Survivable Lightpath Routing for Maximum Logical Topology Capacity and Minimum Spare Capacity Requirements

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***Abstract*—The survivable logical topology mapping problem in an IP-over-WDM optical network is to map each link (u, v) in the logical topology (at the IP layer) into a lightpath between the nodes u and v in the physical topology (at the optical layer) such that failure of a physical link does not cause the logical topology to become disconnected. It is assumed that both the physical and logical topologies are 2-edge connected. For this problem two lines of investigations have been pursued in the literature: one pioneered by Modiano et al., and the other pioneered by Kurant and Thiran. Since then there have been a great deal of research on this problem. Most of the works have not considered limitations imposed on the routings by physical capacity limits. In this paper, we first introduce two concepts: weakly survivable routing and strongly survivable routing. We then provide mathematical programming formulations for two problems. Problem 1 is to design a survivable lightpath routing that maximizes the logical capacity available before and after a physical link failure. The second problem is to add spare capacities to the physical links to guarantee routability of all logical link demands before and after a physical link failure. The frameworks provided by our formulation can be used to accommodate other scenarios such as those involving load balancing and fair capacity allocation constraints. We conclude with simulations that compare the results using these formulations and those obtained by heuristics that mitigate the computational complexity of the mathematical programming formulations.**

I. Introduction

Network survivability is among the most recurring issues when designing telecommunication networks. When a network facility (link or node) fails, a mechanism which guarantees continued network flow and operability is critical. Over the last decade there has been an explosive growth in Internet traffic requiring high transport capacity of telecommunication networks. While the utilization of Wavelength-Division Multiplexing (WDM) extends the capacity of optical fibers [1], optical fiber failures lead to disruptions in traffic and severe consequences. Ramamurthy et al. [2] summarized the protection and restoration mechanisms on WDM networks and examined the routing and wavelength assignment (RWA) problems. With the development of optical cross-connect (OXC) and optical add-drop multiplexer (OADM), WDM is mostly deployed in point-to-point manner and supports multi-layered architectures such as IP/MPLS, ATM, and SONET/SDH [3].

IP-over-WDM network is a two-layered network where an IP (logical) network is embedded onto a WDM (physical) network. IP routers and OXCs correspond to the logical and physical nodes. Links connecting the nodes in a logical network are called the logical links, and the physical links are realized via optical fibers. The logical nodes are commonly assumed to have corresponding nodes in the physical network. On the other hand, not all physical nodes may exist in the logical network. A router-to-router link is implemented through a wavelength on a path between two end nodes in a WDM network bypassing opto-electro-optic (O-E-O) conversions on intermediate nodes in the path. This path is called a *lightpath*. Each optical fiber may carry multiple lightpaths, hence a failure on an optical fiber may have a cascading effect causing failures on multiple logical links, resulting in a huge amount of data traffic (terabytes/sec) loss. This has given rise to an extensive interest in the study of survivability issues in the IP-over-WDM network.

Examples of a survivable mapping and an un-survivable mapping of the links of a logical topology (Fig. 1(a)) onto the links of a physical topology are shown in Fig. 1. In the mapping of Fig. 1(b), when physical link (4,5) fails , logical links (2,4) and (4,6), whose lightpaths are both routed through physical link (4,5), fail simultaneously causing the logical topology to become disconnected since logical node 4 is no longer connected to other nodes in the logical topology after this physical link failure. In contrast, in Fig. 1(c) no physical link failure can disconnect the logical topology, hence the mapping is survivable. Therefore, survivability of a mapping can be guaranteed if the lightpaths in the physical topology corresponding to this mapping are all link-disjoint.

Most previous research concentrated on survivable design of un-capacitated IP-over-WDM networks, while in practice, physical link capacities and logical link demands are usually

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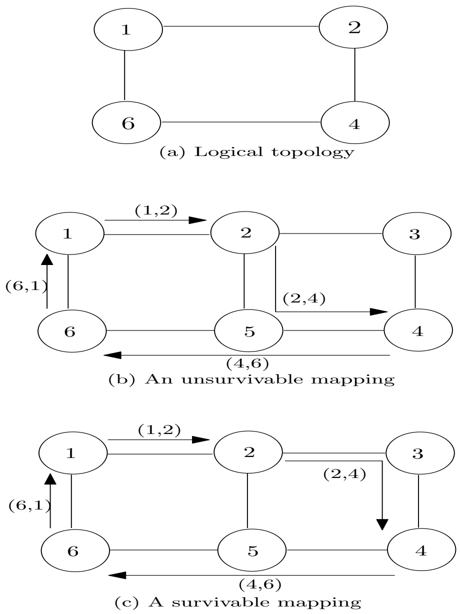

Fig. 1. Un-survivable and survivable mapping for logical topology

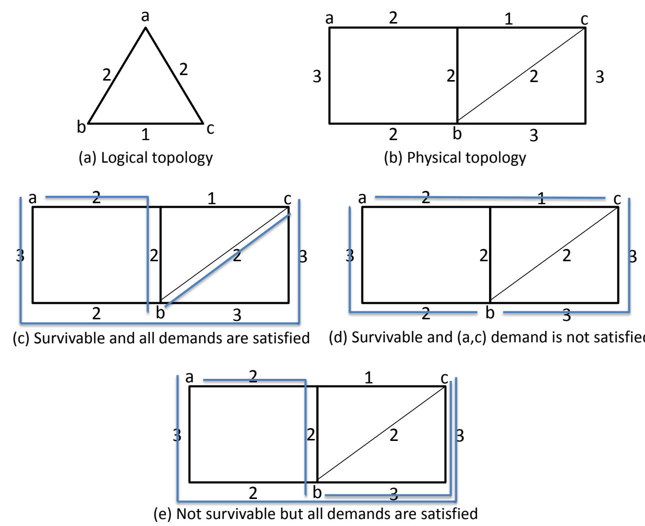

Fig. 2. Capacitated survivability and demand satisfaction

considered during design phase to reduce costs. In the rest of this paper, we consider survivable logical topology design in IP-over-WDM networks with capacity and demand constraints on physical and logical links, respectively. For un-capacitated IP-over-WDM networks, survivability is achieved if the logical network remains connected after any physical link failure. In such a case, since the logical network will be connected after a physical link failure, the existence of alternative lightpaths for the failed logical links is guaranteed. However, if the physical link capacity is taken into consideration, demands on logical links may not be satisfied after physical link failure(s) even if the logical network remains connected. Thus, the original definition of survivability in un-capacitated IP-over-WDM networks does not apply to capacitated networks. In order to satisfy demands on logical links we need to add *spare capacity* to each physical link, which is the extra capacity required to carry the disrupted traffic. Figures 2(a)(b) show a logical network with demands on its links and a physical network with capacities on its links. A survivable routing satisfying both logical link demands and guaranteeing logical graph survivability after a single physical link failure is shown in Fig. 2(c). For the mappings in Figures 2(d)(e), either the logical topology survivability criterion or the logical demand constraints will not be satisfied after a physical link failure.

In this paper we define a capacitated IP-over-WDM network to be *weakly survivable* if there exists a mapping such that the logical network remains connected after a single physical link failure. Note that under weak survivability, not all the logical link demands need to be satisfied after a physical link failure. We define a capacitated IP-over-WDM network to be *strongly survivable* if there exists a logical topology mapping that satisfies two criteria: the logical network remains connected after any physical link failure, and there exists sufficient capacity on physical links to support all disrupted traffic. In this paper, we provide exact Mixed Integer Linear Programming (MILP) formulations and heuristics for the strongly and weakly survivable mappings (equivalently, design) in capacitated IP-over-WDM networks. We also consider the issue of spare capacity assignment at the physical layer to achieve strong survivability.

The rest of the paper is organized as follows. Section II provides a review of literature in the related area. Formal definitions of weak and strong survivability and notations are presented in Section III. This section also defines two classes of problems considered in this paper. Section IV and V provide exact solutions for the two scenarios. We develop heuristics, present experimental settings, and provide a comparative evaluation of the MILP approaches and the heuristics in Section VI. Section VII concludes with problems for further study.

II. Related Work

As we noted in the previous section survivability of a logical topology mapping can be guaranteed if the lightpaths in the physical topology corresponding to this mapping are all link-disjoint. Since finding disjoint paths between pairs of nodes is NP-complete [4], survivable design of the logical topology in an IP-over-WDM network is also an NP-complete problem. Modiano and Narula-Tam [5] proved a necessary and sufficient condition for survivable routing under a single failure in IP-over-WDM networks and formulated the problem as an Integer Linear Program (ILP). Todimala and Ramamurthy [6] adapted the concept of Shared Risk Link Group introduced in [7] and also computed the routing through an ILP formulation. Extensions of the work in [5] are given in [8] and [9]. [8] introduced certain connectivity metrics for layered networks and provided ILP formulations for the lightpath routing problem satisfying these metrics. In particular, they provided approximation heuristics for lightpath routing maximizing the min cross layer cut metric. This metric captures the robustness of the networks after multiple physical link failures. Kan et al. [9] discussed the relationship between survivable lightpath routing and the spare capacity requirements on the logical links to satisfy the original traffic demands after failures. A common drawback of ILP approaches is that they are not scalable as the network size increases. Hence, heuristic approaches that provide approximations to the optimal solutions are presented.

To handle the drawback of ILP approaches Kurant and Thiran [10] proposed the Survivable Mapping by Ring Trimming (SMART) framework which first attempts to find link-disjoint mappings for the links of a subgraph of the given logical graph. If such mappings exist, the subgraph is contracted. The procedure is repeated until the logical graph is contracted to a single node, or at some step disjoint mappings cannot be found. In the former case, the resulting mappings define a survivable mapping of the given logical graph. In the latter case, we conclude that no survivable mapping of the given logical graph exists. Another approach proposed by Lee et al. [11] utilized the concept of ear-decomposition on bi-connected topologies. One can show that this is, in fact, a special variant of the framework given in [10], though it was developed independently. Javed et al. obtained improved heuristics based on SMART [12] [13]. Using duality theory in graphs, a generalized theory of logical topology survivability was given by Thulasiraman et al. [14] [15]. Thulasiraman et al. [16] considered the problem of augmenting the logical graph with additional links to guarantee the existence of a survivable mapping. It has been shown in [16] that if the physical network is 3-edge connected an augmentation of the logical topology that is guaranteed to be survivable is always possible. An earlier work that discussed augmentation is in [17].

There has been a great deal of research on the single layer network survivability problem, in particular, assignment of spare capacities on the physical links to guarantee the required network flows after link failures. Some recent works in this area are [18] and [19]. Some of the other works that studied the spare capacity assignment problem under survivability requirements are [20] and [21]. All these works do not consider the notion of survivability of the logical layer that is critical in IP-over-WDM networks. As remarked earlier, Kan et al. [9] discussed the relationship between survivable lightpath routing and spare capacity requirements on the logical links to satisfy the original traffic demands after failures. In contrast, in this paper we investigate lightpath routing that maximizes the demand satisfaction of the logical graph after failures as well as lightpath routing that minimizes spare capacity requirements on the physical links that guarantees strong survivability as defined in Section I.

III. Problem Description and Notations

We use the terms network and topology, edge and link, node and vertex, interchangeably throughout the paper. Let $G_L = (V_L, E_L)$ be a logical network and $G_P = (V_P, E_P)$ be a physical network in an IP-over-WDM network. Let (i, j) be a physical link and (s, t) be a logical link. Capacity on physical link (i, j) is c_{ij} and demand on logical link (s, t) is d_{st}. We now define the survivability criteria considered in this paper.

First we define *weak survivability* in a capacitated IP-over-WDM network in which logical network is connected but not all demands may be satisfied after any physical link failure. We also define *strong survivability* in capacitated IP-over-WDM networks where two criteria must be satisfied: the logical network remains connected after any physical link failure, and there exists sufficient capacity on physical network to support all disrupted traffic.

Definition 1: An IP-over-WDM network with logical and physical topologies $G_L = (V_L, E_L), G_P = (V_P, E_P)$ is **weakly survivable** if after any physical link failure, G_L remains connected.

Definition 2: An IP-over-WDM network with $G_L = (V_L, E_L), G_P = (V_P, E_P)$, capacity c_{ij} for each physical link (i, j) and demand d_{st} for each logical link (s, t) is **strongly survivable** if after any physical link (i, j) failure, G_L remains connected and d_{st} can be satisfied for all $(s, t) \in E_L$.

Definition 3: The **spare capacity** on a physical link is the extra capacity required to satisfy all d_{st} after any (i, j) failure while the logical topology remains connected. Note: If the spare capacity requirement on each physical link is zero after a physical link failure, then the network is strongly survivable.

We will propose mathematical programming formulations for the following problems:

Problem 1: Determine a lightpath routing that guarantees weak survivability and maximizes the logical link demand satisfaction after a physical link failure.

Problem 2: Determine a lightpath routing that guarantees strong survivability under minimum spare capacity requirements.

Both the weakly survivable and strongly survivable design problems in the IP-over-WDM networks are NP-hard problems. To tackle the problems proposed, we follow a two-stage design approach. In the first stage we determine a lightpath routing that guarantees weak survivability that maximizes logical link demand satisfaction before any physical link failure. In the second stage the two problems proposed above are considered. Next we introduce in Table I the variables used in the formulation.

IV. Weakly Survivable Routing and Maximizing Routable Logical Link Demands

In the section we investigate Problem 1, namely, lightpath routing that guarantees weak survivability and maximizes the logical link demands that are satisfied after any physical link failure. Towards this goal we proceed in two stages.

Stage 1: We design the IP-over-WDM network such that the logical topology remains connected after any physical link failure with the objective of maximizing the logical capacity (logical demands routable under the selected lightpath routing). Higher logical capacity reflects that there is a better

TABLE I
VARIABLES USED IN MILP FORMULATION

Variable	Description	Info.
y_{ij}^{st}	binary variable indicates whether the logical link $(s,t) \in E_L$ is routed through the physical link $(i,j) \in E_P$. If yes, $y_{ij}^{st} = 1$, otherwise, $y_{ij}^{st} = 0$.	first stage for Problem 1.
f_{ij}^{st}	flow on physical link (i,j) due to lightpath (s,t)	first stage for Problem 1.
r_{st}^{ij}	fractional variable for connectivity constraints.	first stage for Problem 1.
ρ_{st}	the capacity for the logical link (s,t), where ρ_{st} is the smallest capacity of links in the lightpath.	first stage for Problem 1.
θ	variable for max single logical link capacity.	first stage for Problem 1.
c_{ij}	capacity on the physical link (i,j).	given.
d_{st}	demand for the logical link (s,t).	given.
u_{ij}	link utilization request on the physical link (i,j)	given.
λ_{ij}^{st}	maximal flow for logical link (s,t) after a physical link failure and re-routing	second stage for Problem 1.
$x_{k\ell ij}^{st}$	rerouted flow on (k,ℓ) which can be maintained after the physical link (i,j) failure and re-routing.	second stage for Problem 1.
$z_{k\ell ij}^{st}$	binary variable indicates whether (s,t) re-route through (k,ℓ) after (i,j) failure.	second stage for Problem 1.
η_{ij}	amount of spare capacity required on the physical link (i,j) to satisfy strong survivability	second stage of Problem 2.
M	a large positive number	Problem 1.

chance that the demands can be satisfied after a physical link failure.

Stage 2: With the information of existing lightpaths and the physical link failure, the demands/flow on the failed lightpaths need to be rerouted and the objective is to minimize the maximum of the unsatisfied demands caused by each physical link failure.

We next discuss an MILP formulation of Problem 1. The first stage constraints provide lightpath routing for each logical demand that satisfies physical link capacity constraints and keeps the logical network connected after any physical link failure. A logical link representing a demand between nodes s and t will be denoted by (s,t) if $s < t$, otherwise by (t,s). The constraints and optimization objective of the first stage of Problem 1 are given in Table II. We formulate the first stage constraints as follows.

Lightpath constraints (1) - (3) guarantee a single lightpath for each logical link (s,t). This is achieved by requiring the binary decision variables y_{ij}^{st} to satisfy the flow constraints. The physical links for which $y_{ij}^{st} = 1$ define a single lightpath for each logical link (s,t).

Proposition 1: The flow equivalence constraint (4) forces flows to be the same for all the physical links on the lightpath selected for the demand d_{st} on link (s,t).

Proof: We prove this proposition by considering 3 cases: 1) both (k,ℓ) and (p,q) are in the lightpath (s,t), 2) one of (k,ℓ) and (p,q) is in the lightpath (s,t), and 3) none of (k,ℓ) and (p,q) is in the lightpath (s,t).

TABLE II
ALGORITHM WSRD-CC FOR WEAKLY SURVIVABLE ROUTING DESIGN UNDER CAPACITY CONSTRAINTS (FIRST STAGE OF PROBLEM 1).

Lightpath constraint:

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = 1, \text{if } s = i, (s,t) \in E_L \quad (1)$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = -1, \text{if } t = i, (s,t) \in E_L \quad (2)$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(j,i)\in E_P} y_{ji}^{st} = 0, \text{ otherwise}, (s,t) \in E_L \quad (3)$$

Capacity constraint (4)-(10):

Flow equivalent constraint:

$$f_{k\ell}^{st} + M(y_{k\ell}^{st} - 1) \le f_{pq}^{st} + M(1 - y_{pq}^{st}), \quad (4)$$
$$(s,t) \in E_L, (k,\ell), (p,q) \in E_P, (k,\ell) \ne (p,q)$$

Flow conservation constraint:(f_{ij}^{st} is the flow on physical link (i,j) due to lightpath (s,t))

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = \rho_{st}, \text{ if } s = i, (s,t) \in E_L \quad (5)$$

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = -\rho_{st}, \text{ if } t = i, (s,t) \in E_L \quad (6)$$

$$\sum_{(i,j)\in E_P} f_{ij}^{st} - \sum_{(j,i)\in E_P} f_{ji}^{st} = 0, \text{ otherwise}, (s,t) \in E_L \quad (7)$$

$$\rho_{st} \le d_{st}, \quad (s,t) \in E_L \quad (8)$$

Bounded flow constraint:

$$(f_{ij}^{st} + f_{ji}^{st}) \le M y_{ij}^{st}, (i,j) \in E_P, (s,t) \in E_L \quad (9)$$

Capacity constraint:

$$\sum_{(s,t)\in E_L} (f_{ij}^{st} + f_{ji}^{st}) \le c_{ij}, (i,j) \in E_P \quad (10)$$

Survivability constraint:

$$\sum_{(s,t)\in E_L} r_{st}^{ij} - \sum_{(t,s)\in E_L} r_{ts}^{ij} = -1, \quad \text{if} \quad s = v_1, (i,j) \in E_P \quad (11)$$

$$\sum_{(s,t)\in E_L} r_{st}^{ij} - \sum_{(t,s)\in E_L} r_{ts}^{ij} = \frac{1}{|V_L| - 1}, \text{otherwise}, (i,j) \in E_P. \quad (12)$$

$$0 \le r_{st}^{ij} \le 1 - (y_{ij}^{st} + y_{ji}^{st}), (i,j) \in E_P, (s,t) \in E_L. \quad (13)$$

$$0 \le r_{ts}^{ij} \le 1 - (y_{ij}^{st} + y_{ji}^{st}), (i,j) \in E_P, (s,t) \in E_L. \quad (14)$$

First stage MILP formulation for the weakly survivable routing design (objective: maximize total logical link capacity):

$$\max \sum_{(s,t)\in E_L} \rho_{st} \quad (15)$$

$s.t.$ Constraint (1) to (14),

$$y_{ij}^{st} \in \{0,1\}, r_{ij}^{st} \ge 0, f_{ij}^{st} \ge 0, \rho_{st} \ge 0 \;\; (i,j) \in E_P, (s,t) \in E_L \quad (16)$$

First stage MILP formulation for the weakly survivable routing design (objective: maximize capacity on a single logical link):

$\max \theta$

where $\theta \le \rho_{st}$. (17)

Congestion constraint (optional):

$$\sum_{(s,t)\in E_L} (y_{ij}^{st} + y_{ji}^{st}) \le u_{ij}, \qquad (i,j) \in E_P \quad (18)$$

For case 1, both (k,ℓ) and (p,q) are in the lightpath (s,t). Then, both $y^{st}_{k\ell}$ and y^{st}_{pq} are equal to 1. Therefore, this constraint forces $f^{st}_{k\ell}$ and f^{st}_{pq} to be equal for every pair of links (k,ℓ) and (p,q) in the lightpath (s,t).

For case 2, one of (k,ℓ) and (p,q) is in the lightpath for (s,t). Then, one of $y^{st}_{k\ell}$ and y^{st}_{pq} equals 1. If $y^{st}_{k\ell}=1$ and $y^{st}_{pq}=0$, then $f^{st}_{k\ell}\leq M$ because $f^{st}_{pq}=0$. If $y^{st}_{k\ell}=0$ and $y^{st}_{pq}=1$, then $f^{st}_{k\ell}=0$ and $f^{st}_{pq}\geq 0$. Thus, this constraint holds.

For case 3, none of (k,ℓ) and (p,q) is in the lightpath for (s,t). Then, both $f^{st}_{k\ell}$ and f^{st}_{pq} are 0 due to $y^{st}_{k\ell}=y^{st}_{pq}=0$. Thus this constraints holds.

Thus we have shown that constraint (4) guarantees the flows to be the same for all the physical links on the lightpath selected for routing the demand on link (s,t). □

Flow Conservation Constraints (5) - (8): These constraints require the flows on links selected for the lightpath (s,t) to be less than or equal to d_{st}.

Bounded flow constraint (9): Constraint (9) guarantees that each physical link carries flow only if the lightpath(s) route through the physical link.

Capacity Constraints (10): Constraint (10) requires that the total flow in each physical link due to all the lightpaths be no more than the corresponding link capacity.

Survivable constraints (11) - (14): Because of the exponential number of constraints involved in the ILP formulation of [5] we have chosen the survivability constraints given in [22]. The constraints (11) - (14) guarantee that if the physical link (i,j) fails then the surviving logical links can support an amount $1/(V_L-1)$ of flow from all nodes to node v_1 guaranteeing that the logical network will remain connected after the physical link failure.

With above constraints, the MILP formulation for the first stage of Problem 1 is in (1) - (16).

There are different ways to evaluate the largest capacity on the logical links. (15) requires maximization of the total capacity on the logical network. We also can maximize the largest capacity on the single logical link by maximizing the minimum capacity on the logical link as in (17).

From the first stage of Problem 1 (WSRD-CC algorithm) we obtain the lightpath routing information with the optimal solution y^*. We consider the second stage of this network design with respect to y^* and ρ^*.

Once a physical link (i,j) fails, we need to re-route lightpaths that were routed through link (i,j) to satisfy at least partially original demands on these lightpaths. With y^*, we know that if $y^{st*}_{ij}=1$, then lightpath $s-t$ is routed through (i,j). Thus, for a given (i,j), we only need to re-route lightpaths that are in the set $R_{ij}=\{(s,t): y^{st*}_{ij}=1\}$. Therefore, in the second stage, after any physical link (i,j) failure, the disrupted network flow is re-routed through a new lightpath going through physical links with enough residual capacities (the residual capacity on physical links before any physical link failure). The existence of the new lightpath routing is restricted by the residual capacities. We formulate the second stage constraints as follows:

TABLE III

ALGORITHM MAXCAP-WSRD FOR SECOND STAGE OF PROBLEM 1

Re-routing constraint: For all $(i,j)\in E_P$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = 1, \quad (19)$$

if $s=k, (s,t)\in R_{ij}$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = -1, \quad (20)$$

if $t=k, (s,t)\in R_{ij}$

$$\sum_{(k,\ell)\in E_P\setminus\{(i,j)\}} z^{st}_{k\ell ij} - \sum_{(\ell,k)\in E_P\setminus\{(i,j)\}} z^{st}_{\ell kij} = 0, \quad (21)$$

otherwise, $(s,t)\in R_{ij}$

Residual capacity constraint: For all $(i,j)\in E_P$

$$\sum_{(s,t)\in R_{ij}} (x^{st}_{k\ell ij}+x^{st}_{\ell kij}) \leq c_{k\ell} - \sum_{(u,v)\in E_L\setminus R_{ij}} \rho^*_{uv} y^{uv*}_{k\ell} \quad (22)$$

$(k,\ell)\in E_P\setminus\{(i,j)\}$

$$x^{st}_{k\ell ij}\leq M z^{st}_{k\ell ij},\ (s,t)\in R_{ij},\ (k,\ell)\in E_P\setminus\{(i,j)\} \quad (23)$$

$$\lambda^{st}_{ij}\geq x^{st}_{k\ell ij},\quad (s,t)\in R_{ij},(k,\ell)\in E_P\setminus\{(i,j)\} \quad (24)$$

$$\lambda^{st}_{ij}\leq x^{st}_{k\ell ij}+M(1-z^{st}_{k\ell ij}) \quad (25)$$

$(s,t)\in R_{ij},(k,\ell)\in E_P\setminus\{(i,j)\}$

Flow equivalence constraint:

$$x^{st}_{k\ell ij}+M(z^{st}_{k\ell ij}-1)\leq x^{st}_{pqij}+M(1-z^{st}_{pqij}) \quad (26)$$

$(s,t)\in R_{ij},(k,\ell),(p,q)\in E_P\setminus\{(i,j)\}$

Algorithm MAXCAP-WSRD (Second stage of Problem 1)MILP formulation for the weak survivability design (objective: max demand satisfaction)

$$\max \sum_{(s,t)\in E_L}\sum_{(i,j)\in E_P}\lambda^{st}_{ij} \quad (27)$$

$s.t.$ Constraints (19) to (26)

$z^{st}_{k\ell ij}\in\{0,1\},\lambda^{st}_{ij},x^{st}_{k\ell ij}\geq 0$

$$(i,j)\in E_P,(s,t)\in E_L,(k,\ell)\in E_P\setminus\{(i,j)\} \quad (28)$$

Re-routing constraint (19) - (21) provide the new lightpaths for logical links which are broken after the (i,j) failure. The demands on the physical links that lie on these new lightpaths must be within their residual capacities.

The residual capacity of the physical link (k,ℓ) is $c_{k\ell}-\sum_{(u,v)\in E_L\setminus R_{ij}}\rho^*_{uv}y^{uv*}_{k\ell}$.

Residual capacity constraint (22) restricts the total rerouted flow on link (k,ℓ) to be within its residual capacity.

Constraints (23) - (26) guarantee that the demand d_{st} rerouted along the lightpath for a broken logical link (s,t) due to the failure of physical link (i,j) is equal to the flows on the links of the lightpath. Constraint (23) restricts the flow on link (k,ℓ) due to the rerouting of the disrupted flow for (s,t) after the physical link (i,j) failure. Here M is a large number greater than the maximum link capacity.

The goal for the second stage of Problem 1 is to minimize the total unsatisfied demand, or equivalently, maximize the total fulfilled demand in the capacitated IP-over-WDM network by appropriately rerouting after a failure occurs. The MILP formulation of the second stage of Problem 1 (called algorithm

MAXCAP-WSRD) is listed in (19)-(28).

V. Strongly Survivable Lightpath Routing under Minimum Spare Capacity Requirements

In this section we investigate Problem 2 which requires the design of a strongly survivable lightpath routing that does not violate physical link capacity requirements. While doing so, we may have to add additional capacity (called spare capacity) to some of the physical links so that all the logical demands can be fully routed. Our objective is to minimize the total spare capacity added.

Towards the above objective we proceed in two stages.

Stage 1: We determine a weakly survivable lightpath routing. Note that such a routing ensures that the logical network remains connected after any physical link failure.

Step 2: Add spare capacity to the physical links and re-route the flows on logical links that are broken due to a physical link failure. This is to ensure that all the logical demands are satisfied after a physical link failure. Our objective is to minimize the total spare capacity required.

The MILP formulation for the design of a strongly survivable routing requiring minimum spare capacities for rerouting the failed logical demands in SSRD-MSC algorithm is given in Table IV.

TABLE IV
Algorithm SSRD-MSC for Strongly Survivable Routing Under Minimum Spare Capacity Requirements

Stage 1:

$$\max \sum_{(s,t)\in E_L} \rho_{st} \quad (29)$$

$s.t.$Constraint (1) to (14), (16)

Stage 2:

$$\min \sum_{(i,j)\in E_P} \eta_{ij} \quad (30)$$

$s.t.$Constraints (19) to (21), (23) to (26),

$$\sum_{(s,t)\in R_{ij}} d_{st}(z^{st}_{k\ell ij} + z^{st}_{\ell kij}) \leq c_{k\ell} - \sum_{(s,t)\in E_L\setminus R_{ij}} \rho^*_{st} y^{st*}_{k\ell} + \eta_{k\ell} (22^{'})$$

$(i,j)\in E_P, (k,\ell)\in E_P \setminus (i,j)$

VI. Simulation and Experimental Evaluation

In this section we report some preliminary results on the effectiveness of our formulations. Due to limitations on the size of the paper, we report results of only a few of our experiments.

We used CPLEX 12.1 to run the weakly and strongly survivable MILP formulations. We adopted the networks introduced in [23] as physical topologies (Networks 2 and 7 (European 1 and 2), and Networks 3 and 6). We also generated a SMALL network with 4(3) nodes and RAND (random network) with 25(12) nodes in the physical(logical) topology. Corresponding logical topologies are chosen to be two-connected. Logical nodes are subsets of physical nodes, that is, $|V_L| = 0.5 * |V_P|$.

Due to limitations on the size of the paper, we report results of only of our experiments on the topologies shown in Tables V and VI. As expected, MILP formulations require high execution times, though they give optimum values of the required results. We compared the results of MILP formulations with certain heuristics that take comparatively smaller execution times. The heuristics were implemented using LEMON library [24].

A brief outline of the methods used for the heuristics are discussed next.

Stage 1 of Problem1:

The heuristic algorithm for the weakly survivable routing problem is as follows. We define a logical node with the maximum degree as the datum node denoted Δ. Pick any logical node v with degree ≥ 2 and map two of v's adjacent edges into disjoint paths in the physical topology, and then remove v and all its adjacent nodes from the logical topology. This procedure is repeated until no logical nodes with degree ≥ 2 is left. Next, pick a node v from the remaining logical topology with degree = 1 (an edge (u, v)), add a parallel edge $(u, v)^{'}$ to (u, v) and then find disjoint mappings for (u, v) and $(u, v)^{'}$ in the physical topology. This procedure is executed until all logical nodes with degree = 1 are eliminated. If after the previous steps, there exist nodes v with degree = 0, add two parallel edges connecting v and Δ and map them disjointly in the physical topology. The augmented logical topology is denoted as $\mathbb{L}$.

The above procedures generate a survivable routing for the augmented logical topology. Proof of correctness of this may be found in our work [16].

We next push a flow of value d_{st} along the lightpath that corresponds to the logical link (s, t) for each $(s, t) \in \mathbb{L}$. The physical link capacities required to satisfy the specified logical demands d_{st} are used as the given physical link capacities. Thus at the end of the first stage we will have a logical topology that has a survivable lightpath routing and physical link capacities that accommodate all the logical demands.

Stage 2 of Problem 1:

In this stage we take down each physical link (i, j) (representing the link failure) one at a time. The lightpaths (the corresponding logical links) that use this link will be broken. Let R_{ij} be the set of logical links that are broken due to the failure of physical link (i, j). We then calculate the residual capacity available on each physical link after the failure of (i, j). For each logical link in R_{ij} we find a new lightpath that avoids the physical link (i, j). We choose a path in the physical topology with the largest residual capacity as the new lightpath. If the logical demand can be satisfied by the new lightpath, the demand is subtracted from the capacity of the links on the lightpath and this demand (s, t) is marked as fully satisfied after failure. Otherwise, we calculate the largest possible demand which can be satisfied and push that as flow on the lightpath and subtract it from the capacity of physical links on the lightpath. Every time we calculate this new logical demand, we also recalculate the residual capacities on the physical links in the selected lightpath.

Stage 1 of Problem 2 is the same as the stage 1 in the case

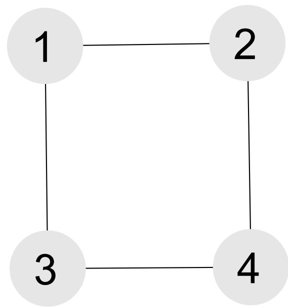

Fig. 3. SMALL network

TABLE V
COMPARISON OF MILP AND HEURISTIC RESULTS ON DEMAND SATISFACTION AFTER FAILURE (WEAKLY SURVIVABLE)

	SMALL	G3	G6	EURO 1	EURO 2	RAND
MILP	0/28	38/38	69/71	17/17	45/47	361/387
Ratio	0%	100%	97%	100%	96%	93%
Heuristic	0/28	32/36	44/62	10/17	41/47	317/372
Ratio	0%	89%	71%	59%	87%	85%

of Problem 1.

Stage 2 of Problem 2:

In this stage we can take down each physical link (i, j) (representing the link failure) one at a time. Using the information about the lightpaths generated in stage 1, we calculate the residual capacities available on the physical links after the failure of (i, j). For each failed logical link (s, t) we find a new lightpath that avoids the physical link (i, j). We choose the new lightpath which has the maximum residual capacity and record the extra capacities required on the physical links to satisfy d_{st} if d_{st} is larger than the residual capacity on the chosen lightpath.

The results of these heuristics are compared with the result of the MILP formulations as in Tables V - VI. Table V compares the total demands satisfied in each case after a physical link failure. The two values, for example, 69/71 in the MILP result of Network 6 (G6), denote that 69 out of 71 affected demands can be satisfied. Notice that the number of total affected demands are different for MILP and heuristic results because the lightpath routings generated are different. From the result we can see that different lightpath routes for the MILP and the heuristic have a strong impact on the satisfied demands after failure. The trade-off between the MILP and heuristic approach is that the computation time for the heuristic is about 50 times less than that for the MILP even on a physical topology with a few dozen nodes, while at the same time the heuristic provides a result which is close to the optimal solution.

Table VI compares the minimum spare capacity required by applying MILP and heuristic approaches. From the table we can see that our heuristic for the strongly survivable case can actually provides a result very close to the optimal solution (or even the optimal solution).

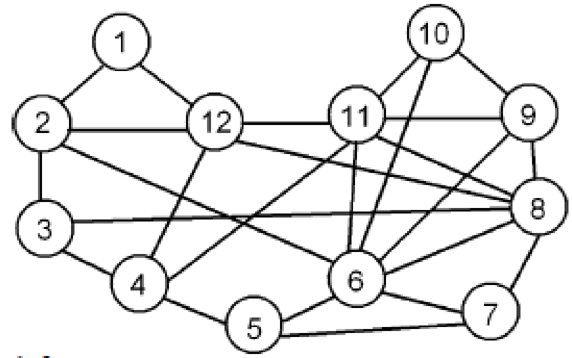

Fig. 4. Network 3 (G3)

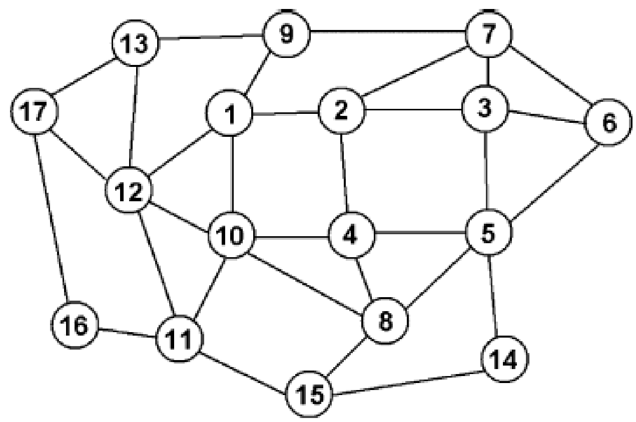

Fig. 5. Network 6 (G6)

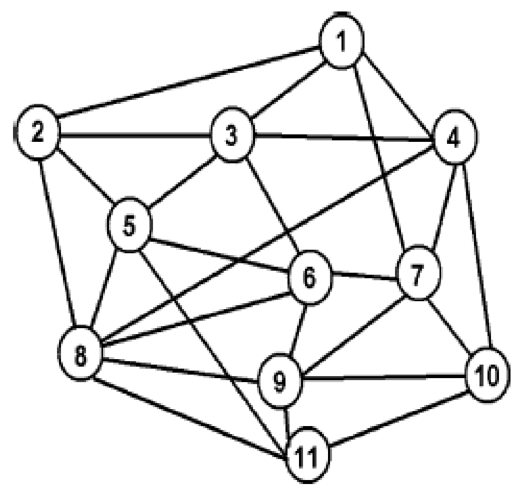

Fig. 6. European Network (EURO 1)

TABLE VI
COMPARISON OF MILP AND HEURISTIC RESULTS ON MINIMUM SPARE CAPACITY (STRONGLY SURVIVABLE)

	SMALL	G3	G6	EURO 1	EURO 2	RAND
MILP	26	3	17	10	6	2
Heuristic	26	3	21	12	6	18

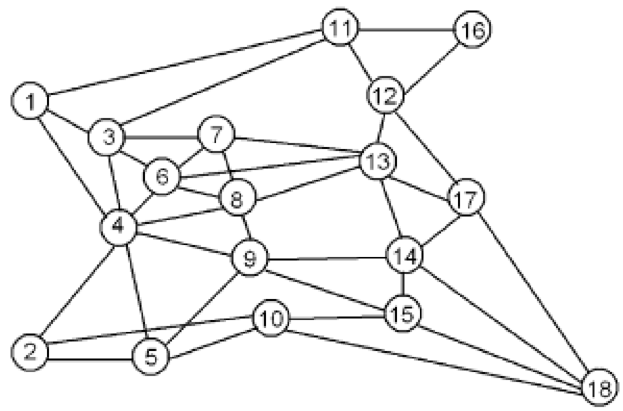

Fig. 7. European Network (EURO 2)

VII. Conclusion

In this paper, we studied generalized versions of the survivable lightpath routing of the logical topology in an IP-over-WDM optical network. Specifically, we define the concepts of weakly survivable lightpath routing, and strongly survivable routing in a capacitated network. We studied two problems. Problem 1 is to determine a lightpath routing that guarantees weak survivability and maximizes the logical link demands satisfaction after a physical link failure. Problem 2 is to determine a lightpath routing that guarantee strong survivability under minimum spare capacity requirements. For both these problems we provided MILP formulations. These formulations provide general frameworks that can be used to accommodate other scenarios such as those involving load balancing and fair capacity allocation constraints. Since MILP formulations require excessive computational time, we described heuristics for both these problems that will be effective in the case of large scale networks. We provided a comparative evaluation of the MILP formulations and our heuristics. Practical networks are adopted as the physical topologies in our experimental design. Due to space limitations only a few of our experimental results have been presented in this paper. We observed that in most cases our heuristics have provided results that are very close to the optimal solution, while consuming much less computation time and also memory space even for graphs with a few dozen nodes. Thus our heuristics are suitable and effective for studying large scale problems. Further investigations along similar lines are under way for the general survivable lightpath routing problem when multiple physical link failures occur.

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