Design of a Survivable VPN Topology over a Service Provider Network

(Invited Paper)

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***Abstract*—Survivability in IP-over-WDM networks has already been extensively discussed in a series of studies. Up to date, most of the studies assume single-hop working routing of traffic requests. In this paper, we study the multi layer survivable design of a logical topology in the context of multiple-hop working routing for IP layer traffic requests. The design problem is composed of two problems which are simultaneously solved: (*i*) Finding the most efficient or economical multi-hop routing of the IP traffic flows with different bandwidth granularities over the logical topology, which involves some traffic grooming, (*ii*) Ensuring that the logical topology is survivable throughout an appropriate mapping of the logical links over the physical topology, if such a mapping exists.**

In order to solve such a complex multi layer resilient network design problem, we propose a column generation ILP model. It allows exploiting the natural decomposition of the problem and helps devising a scalable solution scheme.

We conducted numerical experiments on a German network with 50 nodes and 88 physical links. Not only we could solve much larger data instances than those published in the literature, but also observe than multi-hop routing allows a saving of up to 10% of the number of lightpaths, depending on the traffic load.

I. Introduction

Global broadband traffic doubles every 12 months, and video services, which are slowly but surely engulfing network bandwidth, put pressure on transport line capacity and present processing challenges for IP backbone network nodes. All these indicate that the IP backbone network is stepping firmly into the Tbit/s era. As IP backbone network traffic shifts to Tbit/s, IP backbone network architectures are evolving. The two-layer networking mode ”IP over WDM” is gradually replacing the traditional three-layer ”IP over SDH over WDM” mode to flatten network structure.

In parallel to the evolution of IP backbone networks ”IP over WDM” to ”IP over switched WDM”, network virtualization [1] is also emerging by decoupling the roles of the traditional Internet service providers (ISPs) into two independent entities: infrastructure providers, who manage the physical infrastructure, and service providers, who create virtual networks by aggregating resources from multiple infrastructure providers and offer end-to-end services.

Within that context, the layer 1 VPN (L1VPN) framework [2] emerged in recent years from the need to extend layer 2/3 (L2/L3) packet switching VPN concepts to advanced circuit switching.

The Layer 1 Virtual Private Network (L1VPN) technology supports multiple user networks over a common carrier transport network, and offers a secure and cost effective solution for enterprises and institutional users. It is a VPN whose data plane operates at layer 1, i.e., a service offered by a core layer 1 network to provide layer 1 connectivity between two or more customer sites, and where the customer has some control over the establishment and type of the connectivity. For example a large company with offices in different locations can lease the necessary bandwidth channels directly from WDM-layer network providers. The bandwidth requirement for IP traffic layer, which can be either of multiple or sub-wavelength granularity, is provided by building a Layer-1 VPN over the physical infrastructure of the network provider. Layer-1 VPNs allow different users to share the same physical infrastructure for a fraction of the bandwidth cost of leasing one or several wavelengths.

L1 VPNs need to be resilient, and it is well known that network failures, such as physical link or node failures, cannot be fully avoided when it comes to network management. Consequently, network survivability implies network connectivity after any failure against which a service/network provider wants to be protected. When a failure occurs, the IP layer traffic needs to be routed through alternative IP paths in order to avoid interruption and data loss. Depending on whether the construction of alternative paths is online or offline, the corresponding survivability mechanism is referred to as restoration or protection, respectively. Both layers, the logical layer and the optical layer, need to be resilient to failures. Restoration mechanisms are widely deployed at the logical layer, while the optical layer uses both kinds of survivability mechanisms [3]. Protection comes with an additional cost of spare capacity due to pre-planned reservation of backup resources. On the other hand, restoration mechanisms are preferable in terms of resource efficiency if they can provide fast switching of traffic through alternative paths. Although restoration mechanisms do not require pre-planned backup resources, the connectivity of all three layers should be guaranteed in case of a failure occurs even in the bottom layer.

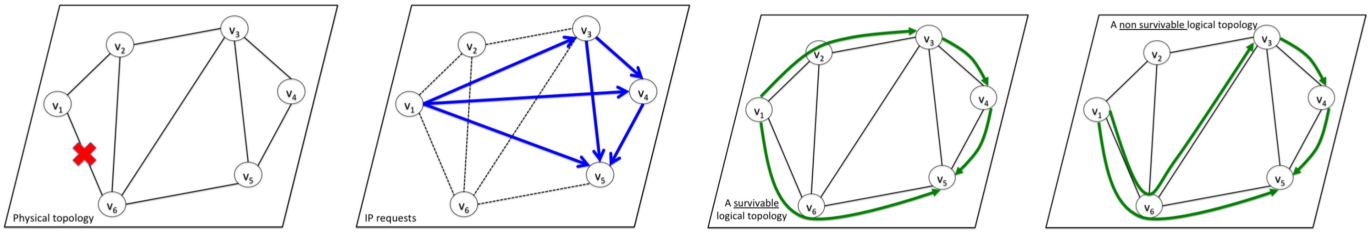

Fig. 1. A L1 VPN network

A network failure, such as a fiber cut, can result in several logical broken links because a given physical resource can be shared among several logical links, which, in turn, can disconnect the logical topology. Hence, the necessary condition for the existence of an acceptable restoration scheme in the logical layer is that the logical topology remains connected (survivable) in case of any network failures [4].

The routing problem in such a multi layer architecture can be divided into two sup-problems. Firstly, there is the mapping of IP traffic flows over the logical topology. This mapping can be single-hop (one demand corresponds to one logical link) if the number of transponders is unlimited or multi-hop (one demand is mapped over a path made of several logical links). Secondly, there is the mapping of logical links over the physical topology. The first sub-problem involves traffic grooming where several sub-wavelength granularity traffic demands can be grouped together to share the capacity of a logical link. The second sub-problem corresponds to the optical layer design problem where we consider survivable routing of lightpaths over a physical topology, with some wavelength assignments.

Most of the previous studies on the survivable logical topology design focus on the second sub-problem, under the assumption that the logical topology is already given. In this paper, we study the multi layer design of a survivable Layer-1 VPN which involves solving simultaneously both sub-problems.

The paper is organized as follows. An illustrative example of the design of a survivable logical topology with multi-hop routing of IP traffic is developed in Section II, together with the motivation of the paper. Literature survey of the recent studies on survivable logical topology design is done in Section III. Section IV presents the detailed problem statement of the Multilayer Survivable Logical Topology Design (MSLTD) problem. We propose a decomposition optimization model in Section V fin order to solve it. Numerical results are presented in Section VIII, together a study of the characteristics of the optimized survivable logical topologies. Conclusions are drawn in the last section.

II. An Illustrative Example

Let us have a look at the example of a L1 VPN in Figure 1. The physical network topology is depicted with black solid lines with 6 nodes and 9 physical links above which a logical network topology is represented in green colored lines with 4 logical nodes and 4 logical links. We also provide the IP layer traffic requests: 6 demands between the four VPN sites. We present two logical topologies, one survivable one, and one non survivable one. Let us consider a first lightpath routing, that maps logical link $v_1 \longleftrightarrow v_3$ with physical path $v_1 \longleftrightarrow v_6 \longleftrightarrow v_3$. This mapping is non-survivable assuming the remaining logical links are mapped as shown in the figure. Indeed, if a physical link occurs on physical $v_1 \longleftrightarrow v_6$, then the two logical links in the upper layer: $v_1 \longleftrightarrow v_5$ and $v_1 \longleftrightarrow v_3$ will be both disrupted. At the top layer, three traffic flows will be interrupted: $v_1 \longleftrightarrow v_3$, $v_1 \longleftrightarrow v_4$, $v_1 \longleftrightarrow v_5$ without any possibility to reroute them as the logical topology is not survivable (not connected). However, if we map the logical link $v_1 \longleftrightarrow v_3$ with physical path $v_1 \longleftrightarrow v_2 \longleftrightarrow v_3$, upon the same fiber cut $v_1 \longleftrightarrow v_6$, the logical topology remains survivable (connected). We can see, for example, the broken logical link $v_1 \longleftrightarrow v_5$ can be restored through logical path $v_1 \longleftrightarrow v_3 \longleftrightarrow v_4 \longleftrightarrow v_5$ and IP traffic layer will not be aware of the failure.

Note also, on this example, that IP requests are not all routed on single hop logical paths. Indeed, in order to limit the number of logical links, assuming bandwidth is available, it is more efficient (less costly in terms of port costs) to route the IP requests from v_1 to v_4 on a 2-hop route.

III. Literature Review

There has been significant amount of work on survivable logical topology design. Some of them start with proposing an ILP (Integer Linear Program) model which can be applied only on small-size topologies or develop heuristics in order to deal with data instances of meaningful sizes.

Modiano and Narula-Tam formulate the first ILP model in [5] focusing on the second sub-problem defined in the previous sub-section. They state a necessary and sufficient condition for a topology to be survivable called cutset theorem which is actually a derived version of the max-flow min-cut theorem.

Todimala and Ramamurthy [6] propose an improvement of the ILP model of [7], under the wavelength continuity assumption, subject to SRLG (Shared Risk Link Groups) constraints. The resulting ILP model is only scalable on particular topologies as its set constraints still include the exponential number of cutsets in the graph underlying the logical topology.

To deal with the complexity of designing survivable logical topologies in IP over WDM networks, Kurant and Thiran [8] introduce a mapping from a logical topology to a simplified one, which preserves survivability. Such a mapping leads them to a heuristic that efficiently searches for a survivable mapping of logical links over the physical topology. Enhancements and evaluations of models derived from [8] are provided in [9], where the authors assume that the selected subgraphs, which are deducted from the logical topology, are cycles.

The SMART framework, proposed in [8], is revisited in [10], and again in [11]. Indeed, Thulasiraman *et al.* [11] show that previously proposed CIRCUIT and CUTSET models in [10], have the same algorithmic structures. This observation leads them to a new generalized CUTSET model which involves both the CIRCUIT and CUTSET models. Experimental results show that the generic CUTSET model works more efficiently than the previous models.

Liu and Ruan [12] consider the survivable mapping problem of IP-over-WDM networks in a more flexible context where several logical links can be added in case no survivable logical mapping can be found for a given logical topology. Again, the proposed ILP model lacks scalability due to the presence of the exponential number of cutset constraints. Similarly, Thulasiraman *et al.* [13] extend their model described in [9] to take into account augmented logical links that can be added to ensure the existence of a survivable routing.

Kan *et al.* [14] study jointly the capacity assignment and survivable logical topology design in IP over WDM networks. Taking into account the spare and working capacity, they derive some cutset constraints to guarantee the survivability of a logical topology. Experiments show that lightpath routing has a significant impact on the spare capacity requirements.

To date, most proposed ILP models are based on the cutset theorem, consequently, possess a huge number of cutset constraints. Thus, these models become intractable when the size of data instance does not correspond to a (very) small network topologies.

Most of the papers consider only the second sub-problem, i.e., survivable mapping of a given logical topology over a physical topology where each demand corresponds to only one logical link. This assumption, however, is not realistic when connection requests arrive as traffic flows in different bandwidth granularities. Let us have a look at a typical example: a global size company requiring bandwidth in different granularities between a set of network sites. In this multi-layer architecture, a logical network of a Layer-1 VPN is setup between several locations. A traffic demand between two locations are routed over several logical links by multi-hop routing.

In [15], Vadrenu *et al.* suggested to use backup capacity of wavelength services to support multi-hop IP traffic so that the bandwidth usage is maximized.

In [16], Cavdar *et al.* study the survivable logical topology design problem in the context of multi-hop routing considering both sub-problems at the same time. The authors present an ILP model which is also based on cutset constraints and solve the problem for only small network instances. Barla *et al.* [17] proposed a MILP model for a very similar problem in the context of cloud services, but again the proposed MILP model lacks scalability in order to solve meaningful data instances.

In this paper, we studied a similar multi-layer survivable design problem, aiming to provide a more scalable solution. Our ILP model can be used for solving much larger network instances than in previous studies.

IV. Problem Statement

The design of a resilient L1 VPN can be described as follows.

Given: *(*i) A physical network topology $G_{\text{P}} = (V_{\text{P}}, E_{\text{P}})$ with V_P denoting the set of physical nodes and E_{P} the set of physical links. *(*ii) The maximum number of wavelengths over one fiber, $W \in \mathbb{Z}^+$. Assuming there is one directional fiber for each physical link, the maximum capacity of a physical link is W units. *(*iii) A set V_{L} of VPN nodes (or logical nodes) between which IP traffic will be exchanged. *(*iv)] A list of IP requests represented by the set $\mathcal{SD} = \{(s,d) : s,d \in V_{\text{L}}\}$ where $\Delta_{sd} \in \mathbb{R}^+$ denotes the amount of traffic needed by demand sd.

Find: *(o)* Logical topology $G_{\text{L}} = (V_{\text{L}}, E_{\text{L}})$ with V_{L} denoting the set of logical (VPN) nodes and E_{L} the set of logical links ; *(oo)* A mapping of the logical links over the set of physical links in such a way that the L1 VPN network remains survivable (i.e. connected) in case of single or multiple failures ; *ooo* A routing of the IP requests over the set of logical links, with single or multi hops
while minimizing the number of lightpaths in the logical topology (primary objective) and the total bandwidth requirement (secondary objective).

Under a multiple link failure scenario, let $\mathcal{F}$ be the set of all possible link failure sets, indexed by F. We assume that all dominated failure sets have been eliminated, i.e., for any F, F' belonging to $\mathcal{F}$, we assume that $F \not\subseteq F'$ and $F' \not\subseteq F$.

The main difference between this problem and the "classic" survivable logical topology design problem for IP-over-WDM networks (for example [5] [18]) is that the granularity of the demands (IP requests) are not of the order of the wavelength granularity, thus traffic grooming is needed for the IP traffic flows. The process of grooming creates another layer, i.e., IP traffic layer on top of physical and logical layers . This layer is responsible for grooming non-integer traffic demands into integer traffic demands before routing integer demands using lightpaths. In addition, the routing of the IP requests does not necessarily corresponds to single-hop logical routes.

An example is given in Figure 2. Green lines are the physical links. We assume bandwidth values to be normalized so that one bandwidth unit corresponds to the wavelength granularity, so that each lightpath has a spare capacity equals to the bandwidth granularity of one wavelength. There are three demands (blue lines) with non-integer bandwidth requirements. Without traffic grooming, we would need 4, 3, 2 units of logical links (red lines) for routing demands d_1, d_2, d_3 respectively. With traffic grooming, 3 bandwidth units of d_1

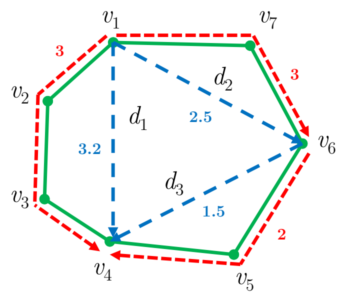

Fig. 2. Grooming with logical topology

are routed via the lightpaths ($v_1 \to v_2 \to v_3 \to v_4$), while the remaining 0.2 unit is groomed with other requests and routed via lightpaths ($v_1 \to v_7 \to v_6$) and ($v_6 \to v_5 \to v_4$) where there is a residual capacity of 0.5. In total, we need 9 lightpaths if there is no grooming and only 8 lightpaths if grooming is used.

V. Optimization Model

The ILP model relies on a decomposition into a set of configurations. Each configuration corresponds to the mapping of a logical link upon the physical topology. More formally, a configuration c is associated with a logical link ℓ'_c and coefficients f^c_ℓ such that $f^c_\ell = 1$ if physical link ℓ is used in the physical mapping logical link ℓ'_c. Parameter a^c_F equals to 1 if ℓ'_c is disconnected following a failure of all the links of $F \in \mathcal{F}$, 0 otherwise. Parameter $\textsc{cost}^c = \sum\limits_{\ell \in E_\text{P}} f^c_\ell$ denote how many units of bandwidth is needed for configuration c. Let $\omega^+_\ell(s)$, $\omega^-_\ell(s)$ be the set of outgoing/incoming logical links of node s respectively. Let $\omega^+_p(s)$, $\omega^-_p(s)$ be the set of outgoing/incoming physical links of node s respectively. A solution is a set of configurations with configuration decision variable $z_c \in \mathbb{Z}^+$ denoting the number of selected copies of configuration c.

This model is constructed based on our previous model in with the following changes: (1) We introduce traffic grooming and allow sub-lambda traffic to model the logical topology (which is assumed given in the previous single-hop routing studies), (2) We change the definition of multi-wavelength-based configurations in [18] to single-wavelength-based in order to increase the scalability of the newly proposed model.

A. Master Problem

The master problem comprises five sets of variables:

- $\phi^{sd}_{\ell'}$ $\in \mathbb{R}^+$, the amount of network flow from v_s to v_d going through logical link ℓ',
- $x_{\ell'}$ $= 1$ if logical link ℓ' is used in virtual topology, 0 otherwise,
- $D_{\ell'}$ $\in \mathbb{Z}^+$ the number of copies of lighpaths corresponding to logical link ℓ'
- z_c number of selected configurations
- $y^F_{\ell'}$ =1 if logical link ℓ' is protected against link failures of F, 0 otherwise.

The objective function is:

$$\min \sum_{\ell' \in E_\text{L}} D_{\ell'} \times \textsc{weight} + \sum_{c \in C} \textsc{cost}^c z_c$$

As we favor minimizing the number of lightpaths over bandwidth requirement, parameter $\textsc{weight} = 10^6$ is added to the objective. Constraints are as follows:

$$\sum_{\ell' \in \omega^+_\ell(s)} \phi^{sd}_{\ell'} = \sum_{\ell' \in \omega^-_\ell(d)} \phi^{sd}_{\ell'} = \Delta_{sd} \qquad (v_s, v_d) \in \mathcal{SD} \qquad (1)$$

$$\sum_{\ell' \in \omega^-_\ell(s)} \phi^{sd}_{\ell'} = \sum_{\ell' \in \omega^+_\ell(d)} \phi^{sd}_{\ell'} = 0 \qquad (v_s, v_d) \in \mathcal{SD} \qquad (2)$$

$$\sum_{\ell' \in \omega^+_\ell(v)} \phi^{sd}_{\ell'} = \sum_{\ell' \in \omega^-_\ell(v)} \phi^{sd}_{\ell'} \qquad v \in V_\text{L} \setminus \{s, d\}, sd \in \mathcal{SD} \quad (3)$$

$$\sum_{sd \in \mathcal{SD}} \phi^{sd}_{\ell'} \leq D_{\ell'} \qquad \ell' \in E_\text{L} \qquad (4)$$

$$\sum_{c \in C : \ell'_c = \ell'} z_c \geq D_{\ell'} \qquad \ell' \in E_\text{L} \qquad (5)$$

$$\sum_{c \in C} f^c_\ell z_c \leq W \qquad \ell \in E_\text{P} \qquad (6)$$

$$\underbrace{\sum_{\ell'' \in \text{CS}(S, V_\text{L} \setminus S), c \in C : \ell'_c = \ell''} a^c_F z_c}_{\text{impaired links going through the cutset}} \leq \underbrace{\sum_{\ell'' \in \text{CS}(S, V_\text{L} \setminus S), c \in C : \ell'_c = \ell''} z_c}_{\text{links going through the cutset}} - x_{\ell'}$$

$$\ell' \in E_\text{L}, S \subset V_\text{L} : \ell' \in \langle S, V_\text{L} \setminus S \rangle, F \in \mathcal{F} \quad (7)$$

$$M x_{\ell'} \geq \sum_{c \in C : \ell'_c = \ell'} z_c \qquad \ell' \in V_\text{L} \qquad (8)$$

$$\sum_{c \in C : \ell'_c = \ell'} z_c \geq x_{\ell'} \qquad \ell' \in V_\text{L} \qquad (9)$$

$$z_c \in \mathbb{Z}^+ \qquad c \in C \qquad (10)$$

$$x_{\ell'} \in \{0, 1\} \qquad \ell' \in E_\text{L} \qquad (11)$$

$$y^F_{\ell'} \in \{0, 1\} \qquad \ell' \in E_\text{L}, F \in \mathcal{F} \qquad (12)$$

$$D_{\ell'} \in \mathbb{Z}^+ \qquad \ell \in V_\text{L} \qquad (13)$$

$$\phi^{sd}_{\ell} \geq 0 \qquad \ell' \in E_\text{L}, (v_s, v_d) \in \mathcal{SD}. \qquad (14)$$

Constraints (1) - (3) are the flow conservation constraints to route the IP layer traffic flows over logical links for each demand sd. Constraints (4) serve to guarantee all traffic flows are satisfied with enough bandwidth. Constraints (5) ensure all logical links are satisfied with enough number of configurations. Constraints (6) limits the number of wavelength over one physical link. Finally constraints (7) are cutset constraints to ensure the survivability of constructed logical topologies. Constraints (8) - (9) serve to identify whether a particular logical link is used in the virtual topology or not.

The above model can be easily modified in order to force single-hop routing by setting $\phi^{sd}_{\ell' : \textsc{src}(\ell') = s, \textsc{dst}(\ell') = d} = \Delta_{sd}$.

VI. Solution of the Optimization Models

A. Column Generation and ILP Solutions

B. Pricing Problem

The pricing problem is to identify the configuration with negative reduced cost. To simplify the notation, we omit the configuration index c in the constraints. For example, f_ℓ should read f^c_ℓ. We also introduce one more variable f^F_ℓ which is defined as the survivable flow when F occurs.

$$\overline{\text{COST}} = \sum_{\ell \in E_{\text{P}}} f_\ell - u^{\text{D}}_{\ell'_c} - u^{\text{W}} f_\ell + u^{\text{M1}} - u^{\text{M2}}$$
$$+ \sum_{S \subset V_{\text{L}}} \sum_{F \in \mathcal{F}} \sum_{\ell' \in CS(S, V_L \setminus S)} \sum_{\ell'' \in CS(S, V_L \setminus S): \ell'' = \ell'_c} u^{\text{F}}_{S,\ell'} (a^F - 1), \quad (15)$$

where u^{D} (resp. $u^{\text{F}}_{S,\ell'}, u^{\text{W}}, u^{\text{M1}}, u^{\text{M2}}$) are the values of the dual variables associated with constraints (5) (resp. (7,6,8,9)).
The logical logical link ℓ'_c is mapped over the physical topology.

$$\sum_{\ell \in \omega^+_P(\text{SRC}(\ell'_c))} f_\ell = \sum_{\ell \in \omega^-_P(\text{DST}(\ell'_c))} f_\ell = 1 \quad (16)$$
$$\sum_{\ell \in \omega^-_P(\text{SRC}(\ell'_c))} f_\ell = \sum_{\ell \in \omega^+_P(\text{DST}(\ell'_c))} f_\ell = 0 \quad (17)$$
$$\sum_{\ell \in \omega^+_P(v)} f_\ell = \sum_{\ell \in \omega^-_P(v)} f_\ell \qquad v \in V \setminus \{\text{SRC}(\ell'_c), \text{DST}(\ell'_c)\} \quad (18)$$
$$f^F_\ell = 0 \qquad F \in \mathcal{F}, \ell \in F \quad (19)$$
$$\sum_{\ell \in \omega^+_P(\text{SRC}(\ell'_c))} f^F_\ell = \sum_{\ell \in \omega^-_P(\text{DST}(\ell'_c))} f^F_\ell = -a^F \qquad f \in \mathcal{F} \quad (20)$$
$$\sum_{\ell \in \omega^-_P(\text{SRC}(\ell'_c))} f^F_\ell = \sum_{\ell \in \omega^+_P(\text{DST}(\ell'_c))} f^F_\ell = 0 \qquad f \in \mathcal{F} \quad (21)$$
$$\sum_{\ell \in \omega^+_P(v)} f^F_\ell = \sum_{\ell \in \omega^-_P(v)} f^F_\ell \quad v \in V \setminus \{\text{SRC}(\ell'_c), \text{DST}(\ell'_c)\} \quad (22)$$
$$f^F_\ell \leq f_\ell \qquad F \in \mathcal{F}, \ell \in E_{\text{P}} \quad (23)$$
$$a^F \in \{0,1\} \qquad F \in \mathcal{F} \quad (24)$$
$$f_\ell \in \{0,1\} \qquad \ell \in E_{\text{P}}. \quad (25)$$

Constraints (16) - (18) are the flow conservation constraints for mapping logical links over the physical topology when there is no failure, while constraints (19) - (22) serve for flow conservation when failure F occurs.

VII. Solution of the Optimization Models

A. Column Generation and ILP Solutions

In order to solve the model with larger instances, we use column generation (CG) techniques to solve the linear relaxations problems. We have already written model the problem in such a way that a solution is a composition of some configurations (i.e., columns). The original problem is divided in two two sub-problems. The problem of finding the optimal coefficients of the columns is called master problem and the problem of generating configuration is called pricing problem. In short, the pricing problem generates promising configurations while the master problem selects the best combination of the generated configurations.

Initially, the master problem contains only some dummy configurations (i.e., the configurations just to make the master problem feasible). At each iteration, the master problem is solved and the dual values are transferred to the pricing problem in order to help the pricing problems to find new "improving" configurations. These configurations if added to the pool of configurations of the master problem can improve the objective function. This process stops when no improving configurations can be generated, meaning that we have found the optimal LP solution. (See, e.g., Chvatal [19] for more detailed explanations)

Once the optimal solution of the linear relaxation $z^\star_{\text{LP}}$ of the problem has been found, we want to derive an integer solution $\tilde{z}_{\text{ILP}}$ such that the optimality gap ($\varepsilon = (\tilde{z}_{\text{ILP}} - z^\star_{\text{LP}}) / z^\star_{\text{LP}}$) is as small as possible. In this study, we use an ILP solver (CPLEX) to find the optimal ILP solution from the set of generated columns. While there is no guarantee about the quality of the ILP solution, in practice CPLEX is able to find good ILP solutions as we will present in Section VIII.

B. Dealing with Exponential Number of Cutset Constraints

Because our model contains an exponential number of cutset constraints, even with CG, it is still impossible to solve the model for meaingful size network instances. To address this issue, we decided to treat the cutset constraints as lazy constraints as we observe the fact that once a few of cutset constraints are satisfied, usually the rest of cutset constraints are also satisfied.

The solution starts with no cutset constraint in the set of constraints. Each time an ILP solution is found, we check whether the solution satisfies all cutset constraints. While there is an exponential number of cutset constraints, the process of finding one violated cutset constraint can be done in polynomial time with a shortest path tree algorithm.

Given an ILP solution, we first identify the list of broken logical links following each each network failure. To check if a broken logical link can be restored via survivable logical link, we start from one end-point of the link, using Depth first search on the survivable links to go to the other end. If the other end is reachable, it means that the logical link is restorable via survivable links. Otherwise, the set of nodes are divided into two groups (one group contains all the reachable nodes and the other group contains the left) and we setup a cutset constraint based that partition.

If there is some violated constraints, we add some (not necessarily all) constraints that are violated by the current ILP solution and solve again the new enriched LP model. Otherwise, we have an ILP solution which satisfies all cutset constraints, even if only a small number of them have been explicitly included in the set of constraints. Figure 3 summarizes the whole process.

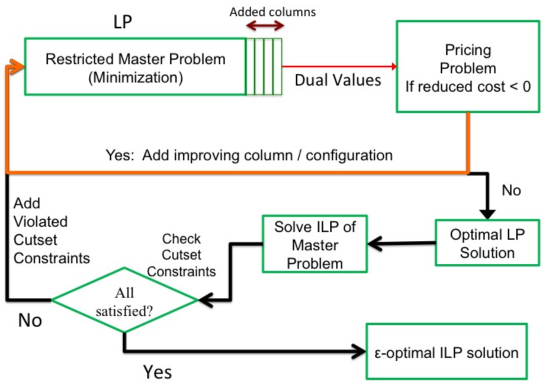

Fig. 3. Solving ILP with Column Generation

VIII. Numerical Experiments

A. Data instances

We conducted experiments on the German network topology [20] with 50 nodes and 166 directional physical links.

We have created two sets of logical nodes, with 11 and 15 nodes respectively, randomly selected among the 50 physical nodes. Associated with the first set of logical nodes, we have generated two different sets of potential logical connections, one with 110, and another one with 60 randomly selected logical connections among the ordered pairs of logical nodes. Note that a connection indicates that two logical nodes are connected in a given direction, with one logical link associated with the connection.

The first set of potential logical connections, with 110 connections, corresponds to the case where all directed pairs of logical nodes are connected. Associated with the second set of nodes, we generated two different sets of potential logical connections, one with 210 and another one with 80 potential logical connections. For each of the four logical topologies, we considered 20 fractional IP traffic demands, each generated between two randomly selected logical nodes, with bandwidth requirements between 1.0 and 10.0 units of bandwidth. We have normalized the sum of those 20 IP demands in order to end up with the same total IP traffic, and we considered three different overall bandwidth values for each different topology, see Table I. We also assume that the wavelength granularity is normalized to 1 bandwidth unit (i.e., is worth 10, or 40 or 100 Gbps). In addition, for each logical topology, and each overall amount of IP traffic, we randomly generated 10 traffic instances.

The LP and ILP models of Section V have been implemented using the optimization programming language (OPL) and solved by CPLEX 12 [21]. The resulting programs have been run on a computer with an AMD Opteron 64-bit processor with 4-cores clocked at 2.2 GHz.

B. Quality of the Solutions

We conducted a first set of experiments in order to evaluate the quality of the solutions, throughout the value of the optimality gap, i.e., the relative difference between a lower bound and an upper bound on the optimal value as given by $z^\star_{\text{LP}}$ and $\tilde{z}_{\text{ILP}}$, respectively:

$$\text{GAP} = \frac{\tilde{z}_{\text{ILP}} = z^\star_{\text{LP}}}{z^\star_{\text{LP}}}.$$

20 IP requests						
# logical		overall traffic amount	GAP %	# cutset constraints	# Config.	
nodes	connections				G	S
11	110	400	1.5	0	34.3	23.7
		300	2.1	0	34.1	23.3
		200	3.1	0	33.7	22.4
	60	200	3.2	6.3	37.5	28.1
		150	4.3	6.1	37.2	27.4
		100	6.1	5.7	37.4	27.5
15	210	800	0.8	0	33.5	24.3
		600	1.5	0	34.1	24.8
		400	2.2	0	33.9	25.1
	80	600	1.6	0	40.2	29.4
		450	2.1	0	41.1	29.7
		300	3.1	0	41.2	29.9

TABLE I
Quality of the Solutions.

Results are presented in Table I. We observe that we are able to obtain ε-solutions with a gap (ε) less than 6%. The number of generated cutset constraints is extremely small in comparison with the overall number of potential ones, which fully justify the use of a ”lazy constraint” strategy in order to handle them. Indeed, in the case of having logical connections between every pair of logical nodes, we do not need to add any cutset constraint. This is because, in these cases, the logical topology is sufficiently dense so that the first solution (without cutset constraints) is already survivable.

In the last two columns, we report the number of generated and selected configurations, respectively. As usually the case when using column generation techniques, the number of generated columns is a very small fraction of the overall number of potential configurations. The number of selected configurations is around 2/3 of the number of generated configurations, meaning that the pricing problem is very efficient in identifying the most promising configurations.

C. Characteristics of the Optimized Logical Topologies

In Table II, we have analyzed different parameters of the generated logical topologies, with different number of logical nodes and potential logical connections.Again, we generated 20 IP requests, under different traffic scenarios, i.e., IP requests with different granularities.

We observe that the number of logical links needed for routing the IP traffic demands is much smaller than the number of potential logical connections. The volume of traffic has no effect on the survivability of the logical topology, since the survivability of the routing is only related to the connectivity aspect, i.e., to the number of IP requests. In the last column, we report the number of lightpaths. Note that each ligthpath is associated with one wavelength (cannot carry more than one

# potential / # logical connections	# survivable topologies	# 1-hop routing (in terms of logical links)	2-hop	3-hop	4-hop	> 4-hop	# logical links	Bandwidth usage
20 IP Requests - Overall amount of traffic: 150 units								
210	10	18.5	0	0.6	0.3	0.6	19.9	95
170	10	18.6	0	0.6	0.3	0.5	19.9	95
130	10	18.7	0	0.6	0.3	0.4	19.9	95
100	10	18.6	0	0.6	0.4	0.4	19.9	95
70	10	18.4	0	0.8	0.3	0.5	19.9	95
60	7	18.6	0	0.7	0.1	0.6	19.9	95
40 IP Requests - Overall amount of traffic: 150 units								
210	10	25.9	0.9	5.1	3.5	4.6	37.9	97
170	10	26.2	0.9	4.9	3.2	4.8	37.9	97
130	10	24.6	0.6	4.8	2.7	5.5	37.9	97
100	10	26.6	1.1	3.7	3.6	5.0	37.9	97
70	7	25.4	1.0	6.0	4.0	3.6	38.0	97
60	5	26.0	1.2	5.8	2.0	5.0	38.0	97
60 IP Requests - Overall amount of traffic: 150 units								
210	10	38.5	2.1	8.7	3.6	6.8	55.3	97
170	10	38.9	2.1	8.0	3.7	7.0	55.3	97
130	10	38.5	2.0	8.6	3.6	7.0	55.3	97
100	10	38.1	1.8	9.2	3.5	7.1	55.3	97
70	3	40.0	2.0	7.3	3.3	7.0	54.3	97
60	2	41.0	2.5	6.0	4.0	6.5	54.5	97

TABLE III
EFFECT OF THE NUMBER OF LOGICAL LINKS ON THE SURVIVABILITY OF THE NETWORK

# logical nodes	potential connections	# traffic units	# survivable topologies	# selected logical links	# lightpaths
11	110	400	10	24	406.7
		300	10	23	306.3
		200	10	22	206.4
	60	200	9.1	28	206.5
		150	9.0	27	157.1
		100	9.1	28	106.4
15	210	800	10	24	810.2
		600	10	25	609.7
		400	10	25	409.8
	80	600	9.2	29	609.1
		450	9.3	30	458.6
		300	9.2	30	308.3

TABLE II
CHARACTERISTICS OF THE GENERATED LOGICAL TOPOLOGIES

unit of traffic). We then observe that the number of lightpaths, while the IP requests may be routed on multi-hop routes, is roughly equal to the number of traffic units.

D. Single/Multi-hop Routes vs. Number of Potential Logical Links

In order to study the effect of the number of logical connections on the survivability of the network and on the number of logical hops of the routes of the IP requests, we conducted experiments in which we gradually reduces the number of potential logical connections, from 210 to 50, in a logical network with 15 randomly selected logical nodes, and 20 to 60 IP requests. Results are shown in Table III.

In terms of the number of survivable topologies also decreases, it stats to decrease when the number of potential connections is below 60 or 70, depending on the number of IP requests.

We can also see that, most of the demands are single hop routing, which is a consequence of the objective of minimizing the number of lightpaths. The very small number of 2-hop routing can be explained by the fact that the probability of having 3 IP demands defining a triangle, so that the granularities are such that one of the IP request can be routed on a two hop route, with each hop being associated with the two other requests, is very small.

The number of hops increases when the number of IP requests increases. Indeed, the percentage of multi-hop logical routes increases from 7% in the case of 20 IP requests to 10% for 40 IP requests and to 35% for 60 IP requests. This is easily explained by the fact that, when the number of IP requests increases, it is easier for an IP request to be routed using other IP request routes.

Since a large number of routes are single hop routes, the number of logical links is fairly close to the number of IP requests as can be seen in the penultimate column. Indeed, we observe a slight increase of the number of logical links when the percentage of single hop routes increases.

Lastly, in the last column, we report the bandwidth usage. It is computed as the ratio of the sum, over all physical links, of the used bandwidth, over the spare bandwidth (considering only the activated wavelengths). We can see that the bandwidth usage is increased when we increase the number of IP requests. Indeed, when the number of IP requests increases, the routing is more efficient leading to a better bandwidth usage.

E. Multi-hop Routing versus Single hop Routing

As mentioned in Section V, the proposed optimization model can also be used to impose single hop routing by setting the logical network flow variables as follow: $\phi^{sd}_{\ell':\text{SRC}(\ell')=s,\text{DST}(\ell')=d} = \Delta_{sd}$. This amounts to forcing the

# potential connected logical connections	Multi-hop routing				Single-hop routing				Difference in the # lightpaths (%)
	# survivable topologies	GAP	# lightpaths	# selected logical links	# survivable topologies	GAP	# lightpaths	# selected pairs of links	
20 IP Requests - Overall amount of traffic: 150 units									
210	10	5.6	158.3	20.0	10	5.7	163.2	20.0	3.1
170	10	5.0	157.8	20.0	10	5.2	163.0	20.0	3.3
130	10	5.1	158.1	20.0	10	5.9	163.1	20.0	3.2
100	10	5.2	158.2	20.0	10	5.4	163.7	20.0	3.5
40 IP Requests - Overall amount of traffic: 150 units									
210	10	6.1	160.0	37.9	10	11.0	167.6	40.0	4.8
170	10	6.7	161.2	37.9	10	11.6	168.5	40.0	4.5
130	10	7.2	161.8	37.9	10	12.0	169.1	40.0	4.6
100	10	7.0	161.5	37.9	10	12.1	169.3	40.0	4.8
60 IP Requests - Overall amount of traffic: 150 units									
210	10	7.0	161.7	55.3	10	17.4	177.3	60.0	9.6
170	10	7.4	162.2	55.3	10	18.2	178.5	60.0	10.1
130	10	8.6	164.1	55.3	10	19.3	180.1	60.0	9.8
100	10	7.8	162.8	55.3	10	18.0	178.3	60.0	9.5

TABLE IV
MULTI-HOP ROUTING VERSUS SINGLE-HOP ROUTING

logical links connecting the two endpoints of an IP request to carry the whole traffic of that demand. Results are shown in Table IV.

We observe that there is a slightly smaller number of lightpaths when switching from single-hop routing to multi-hop routing. This is a consequence of the results observed in Table III with respect to the small number of logical routes with multi hops.

IX. CONCLUSION

We investigated the impact of allowing multi-hop logical routes for IP traffic in a resilient virtual network. Conclusions are that, when the logical topology is resilient, most IP requests are routed on a single hop route, and therefore, the option of logical multi-hop routes has limited interest.

ACKNOWLEDGMENT

The first author has been supported by a Concordia University Research Chair (Tier I) and by an NSERC (Natural Sciences and Engineering Research Council of Canada) grant.

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