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Resource Saving: Which Resource Sharing Strategy to Protect Primary Shortest Paths?

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Abstract—Protection aims to ensure service continuity even upon failure by pre-computing backup paths. To save the network resources while providing protection, two strategies of resource sharing are defined in literature: (1) restrained sharing which limits the resource sharing to the backup paths and (2) global sharing which extends the resource sharing to the primary and backup paths.

In this paper, we study the impact of resource sharing strategies on the resource utilization when the primary paths correspond to the shortest ones according to a strictly positive and static metric. With the single failure assumption, we show formally that the resource sharing between primary and backup paths is limited to some few links which cannot form a backup path. Thus, independently of the amount of resources (for instance: bandwidth) that can be shared between the primary and backup paths, the maximum number of backup paths is bounded. In our simulation, we comfort our formal result by showing that the two strategies have close rates of backup path rejection and backup bandwidth utilization.

I. INTRODUCTION

Today's applications (VoIP, IPTV, etc.) are very sensitive to the disruption of communications and consume more and more resources (such as bandwidth). Hence, protection against failures is becoming very desirable to prevent or reduce the disruption time of communications. However path protection consumes network resources if backup paths are pre-configured and their resource reserved, thus resource optimization is required to improve the network resource utilization.

Network protection [1], [2], [3], [4], [5] maintains the communication service continuity by pre-computing and generally pre-configuring backup paths capable to reroute traffics of affected primary paths upon a failure. To ensure resource availability¹ after a failure repair, the primary and backup paths should reserve their resources. Whereas the primary paths really use the resources they reserved, the backup paths doesn't consume any resources before a failure occurrence. Hence, under the single failure assumption, resources can be shared between all the backup paths which protect against different failure risks, since these backup paths cannot be active at the same time. In addition of the resource sharing, the primary paths should follow the shortest paths in order to achieve resource optimization. For instance, the internet routing protocols (RIP and OSPF) are designed to save resource by allowing the computation of shortest paths.

Recently, more attention was given to the virtual networks. For efficiency, virtual networks are built in a way they consume less resources. Due to the NP-completeness of the the problem of mapping a virtual network to a substrate network (Virtual Network Embedding or VNE), most of the proposed solutions use pre-computed (k-)shortest paths. Like in classical networks, two types of protection could be applied to ensure survivability : global and local. With the global protection, a primary virtual link (which corresponds to a substrate path) is protected by a disjoint backup virtual link connecting the same extremities [5]. Two virtual links are said disjoint if they don't share any link or internal node in the substrat network. With the local protection, each link or node belonging to a substrat primary path (i.e. primary virtual link) is protected locally by a backup path which bypasses it.

To ensure enough resources upon failure, resources must be reserved for the backup paths. As only some backup paths are activated to cope with a single failure, more resources can be saved by sharing them. Two main sharing strategies are defined for this purpose: (1) restrained resource sharing [2] and (2) global resource sharing [1]. With the first strategy, the resource sharing is limited and applied to the backup paths protecting against different failure risks. As these backup paths cannot be active at the same time (due to the single failure assumption), they cannot ask for their resources simultaneously and thus they can share them. With the second strategy, the resource sharing is extended and applied to primary and backup paths. Concretely, since a backup path can bypass several links and/or nodes of a primary path, some resources can be freed on the primary affected paths. Such resources can be reallocated to the backup paths.

In this paper, we study the impact of resources sharing strategies on the resource utilization when the primary paths are the shortest ones. After reviewing works related to the resource sharing in Section II, we introduce and explain in more details the principles of the restrained and global resource sharing strategies. Then, we determine in Section III the formulas computing the amount of sharable and allocated resources with application to the two sharing strategies. In Section IV, we study formally the impact of resource sharing strategies on the resource utilization when the primary paths are the shortest ones. We show that the impact of the primary path resources freed upon a failure is very low and negligible on the protection capability. In Section V, we compare and measure by simulations the gain obtained by global resource sharing

¹In the rest of this document, *resource* refers to *bandwidth*.

instead of restrained resource sharing. Finally, Section VI is dedicated to the conclusions.

II. RELATED WORKS

In the last two decades, a great deal of work is addressing network protection to find efficient algorithms and mechanisms providing survivability and optimizing the resource utilization.

In [6], [7], several network coding-based strategies are described to provide protection in optical and also higher layers. In [8], an extensive survey of the recovery methods is given. These methods are classified according to different criteria such as the *layer* in which recovery methods are applied (Physical, Link, Network, etc.), *computation and/or establishment moment* of the backup paths (before failure for protection and after failure occurrence for the restoration), *resource usage* (without resource sharing or with resource sharing), *scope* (global or local) and *domain* (intra-domain or inter-domain). In MPLS networks, and under different network parameters and constraints, [9], [10] propose various comparison metrics, such as the packet loss, rejection probability and restoration time, to evaluate the level of protection. Unfortunately, neither [9], [10] nor [8] consider global sharing in their studies.

For MPLS networks, global and local protection with/without resource sharing can be applied. With the global protection [2], two disjoint paths connecting the source and target nodes are computed: one primary path used to transmit traffic before any failure and one backup path that should be activated and used for routing upon any failure affecting the primary path. With the local protection [1], [11], [12], for every link and/or node of the primary path, one local backup path bypassing the protected link and/or node is computed. When a failure occurs, the traffic is switched locally at the PLR to the backup paths bypassing the failed risk. In [11], Li et al. proves that joint resource optimization of primary and local backup path is an NP-hard problem.

In last few years, novel protection methods are developed to protect virtual networks [4], [5]. Due to the complexity of the survivable virtual network embedding (SVNE) problem, this later is generally subdivided into two sub-problems (VNE and protection) which can be solved separately. Whereas on-line protection is applied to protect one path in classical networks, many substrat paths (each one corresponds to a virtual link) should be protected together to provide on-line protection in virtual networks. In [5], the authors proposed to protect each primary substrat path (primary virtual link) by a disjoint shortest substrat path. To save resources, the backup paths minimize the additional bandwidth. In [4], the authors propose to protect locally the substrat links which are used to form the virtual links. In their approach, Guo et al. firstly select a subset of primary and backup paths before running a linear program that optimizes bandwidth allocation while balancing the load.

To decrease the rejection rate of protection requests (i.e., to improve the resource utilization), [12] proposes a global resource sharing strategy. Contrarily to the restrained resource sharing strategy which limits the resource sharing to the backup paths, Mélon et al. suggest to pre-allocate the resources freed by the deactivated (or bypassed) primary path segments upon a failure to the backup paths which will be activated to recover from that failure (see Section III). In order to minimize

the resource allocation, [1] proposes a resource sharing-based cost function that measures the amount of extra spare resources required to cross a given link. Obviously, larger are the primary resources freed on a link upon a failure, smaller is the cost of this link for that failure. As this link cost function depends only on the capacities of resource sharing, the backup path and thus the recovery time may be arbitrary long. Indeed, the backup paths optimizing the cost function may include very long paths which induce high transmission delays. In addition, optimizing the resource allocation does not systematically improve the request rejection rate.

Although the primary paths often correspond to the shortest ones, none of the described works studies the impact of such primary routing decision on the blocking probability and the bandwidth sharing capabilities. In this paper, we try fill the gap by studying and measuring the impact of an optimal primary routing (according to a strictly positive and static metric) on the performances of the backup path routing.

III. BANDWIDTH ALLOCATION MODEL

Before the presentation of the path admission control that takes into account bandwidth sharing (section III-A) for path computation, we first give some notations and definitions useful to the understanding of our control admission models (section III-B).

A. Notations

Let us consider a directed graph $G = (V, E, \vec{w}, \vec{C})$ where V is the set of vertices, E the set of links and (\vec{w}, \vec{C}) are functions that associate respectively to each link $(\lambda \in E)$ a strictly positive constant weight $w(\lambda)$ and a bandwidth capacity expressed in bandwidth units C^λ . We define:

- the weight $w(\pi)$ of a primary path π as follows:

$$w(\pi) = \sum_{\lambda \in \pi} w(\lambda).$$
- $Pr_r^{(s,t)}$ as the set of primary paths crossing the failure risk r (link, node or a set of links and/or nodes) and interconnecting the source node s to the target node t . All the paths in $Pr_r^{(s,t)}$ are the shortest ones.
- P^λ as the primary bandwidth that should be reserved on each link λ to carry out traffic before failures. It is computed as the cumulated bandwidth of primary paths crossing the risk λ and connecting s to t .
- $Bp_r^{(s,t)}$ as the set of backup paths protecting the primary paths in the set $Pr_r^{(s,t)}$.
- δ_r^λ as the protection cost of risk r on link λ . It corresponds to the cumulated bandwidth of backup paths which will be activated on link λ to cope with the failure of risk r .
- L_r^λ corresponds to the (primary) bandwidth freed on link λ upon failure of risk r .
- two bandwidth allocation methods on links: bidirectional and unidirectional. With the first method, any two unidirectional links ($u \rightarrow v$ and $v \rightarrow u$) which share the same physical conductor $u - v$ use the same pool for bandwidth allocations. With the second

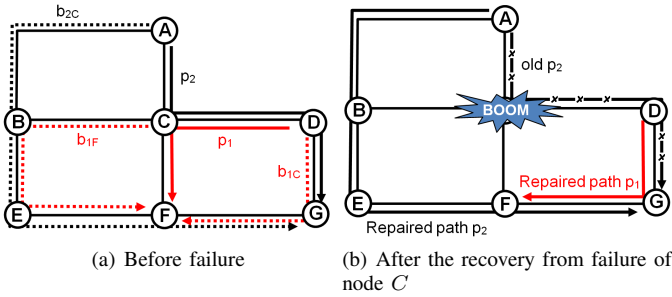


Fig. 1: Protection and bandwidth sharing

bandwidth allocation method, each unidirectional link has its own autonomous pool that it uses for bandwidth allocations.

For the ease of understanding and without loss of generality, we will focus in this paper on the case of unidirectional bandwidth allocations. As the case of bidirectional bandwidth allocations can be treated in the same way, only the results of simulations are given and discussed.

B. Admission control of backup paths

Using local protection mode, regardless of resource sharing strategies, $N - 1$ local backup paths (detours) should be built to protect a path that crosses N nodes. For instance, to fully protect path $p_1 = D \rightarrow C \rightarrow F$ in Figure 1 (a), two backup paths $b_{1C} = D \rightarrow G \rightarrow F$ and $b_{1F} = C \rightarrow B \rightarrow E \rightarrow F$ are established. The first backup path interconnects the PLR node D to the merge node F whereas the second backup path connects the PLR node C to the merge node F . Thus, the first backup path is a NNHOP path protecting against the failures of PLR's downstream node (C) and link ($D - C$) whereas the second backup path is a NHOP path protecting against the PLR's downstream link ($C - F$).

To save resources and accept more path establishment requests, resources like the bandwidth could be shared between paths. For instance, under the practical hypothesis of simple failure adopted in many articles ([1], [4], [11]), some paths cannot carry traffic at the same time: they can therefore share their bandwidth allocations. For this purpose, two main bandwidth sharing strategies were defined: (1) restrained bandwidth sharing and (2) global bandwidth sharing.

With the first bandwidth sharing strategy, the bandwidth sharing is applied and limited to the backup paths that protect against different failure risks. In Figure 1 (a), the backup path b_{2C} ($A \rightarrow B \rightarrow E \rightarrow F \rightarrow G$) protecting the primary path p_2 ($A \rightarrow C \rightarrow D \rightarrow G$) against failures of node C and link $A - C$ can share its resource allocation (for instance, on links $B - E$ and $E - F$) with the backup path b_{1F} ($C \rightarrow B \rightarrow E \rightarrow F$) which protects the primary path p_1 ($D \rightarrow C \rightarrow F$) against the failure of link $C - F$. Indeed, paths b_{2C} and b_{1F} cannot be active at the same time since they protect against disjoint sets of failure risks (failure of link $A - C$ for b_{2C} and, link $C - F$ for b_{1F}). Thus, after determining the protection costs δ_r^λ of risks r on the link λ which correspond to the cumulative bandwidth of backup paths that should be activated to recover from failure r , we determine the protection bandwidth R^λ that

should be reserved for protection on the (unidirectional) link λ as follows:

$$R^\lambda = \max_r \delta_r^\lambda \quad (1)$$

The total bandwidth $bw(\lambda)$ allocated on λ must be always smaller than the capacity C^λ of link λ :

$$bw(\lambda) = P^\lambda + R^\lambda = P^\lambda + \max_r \delta_r^\lambda \leq C^\lambda \quad (2)$$

In addition of the bandwidth sharing between the backup paths, more bandwidth could be saved by reallocating the bandwidth freed by the bypassed part of the primary path upon failure [1]. For instance, to recover from failure of node C in Figure 1 (a), the traffics of the primary paths p_1 and p_2 will be switched to the backup paths b_{1C} and b_{2C} respectively. As shown in Figure 1 (b), the recovery from the failure of node C frees up bandwidth on some primary links. Typically, when node C fails, the traffic of primary path p_2 (old p_2 in Figure 1 (b)) will be switched onto backup path b_{2C} (repaired path p_2 in Figure 1 (b)). Thus, some bandwidth will be freed on link $D - G$ after the node failure recovery. In order to save bandwidth, the global bandwidth sharing strategy proposes to reuse the bandwidth freed up after the recovery of failure r by reallocating it to the backup paths that protect against the same failure r . In our example, the bandwidth allocated on link $D - G$ can be shared between the primary path p_2 and the backup path b_{1C} (see Figure 1 (a)) since these two paths cannot be active on $D - G$ at the same time.

Let us define R^λ as the amount of bandwidth reserved for backup paths:

$$R^\lambda = \max_r (\delta_r^\lambda - L_r^\lambda, 0) \quad (3)$$

We deduce the total amount of bandwidth $bw(\lambda)$ allocated on the link λ as follows:

$$bw(\lambda) = P^\lambda + R^\lambda = P^\lambda + \max_r (\delta_r^\lambda - L_r^\lambda, 0) \leq C^\lambda \quad (4)$$

Although it seems that the global resource sharing strategy is more efficient than the restrained resource sharing strategy, the blocking probabilities of the two strategies could be very close, especially when the primary paths correspond to the shortest ones in terms of a strictly positive and static metric. In the following sections, we prove formally and by simulations that both the two strategies have close blocking probabilities.

IV. IMPACT OF THE AMOUNT OF PRIMARY BANDWIDTH FREED UPON FAILURE ON THE BLOCKING PROBABILITY

The majority of the well known IGP protocols computes the primary paths as the shortest ones in terms of a static metric (i.e., traffic independent costs). For instance, RIP minimizes the hop number while OSPF applies the SPF (shortest path first) algorithm to optimize a static metric that depends generally on bandwidth capacities of links. For VNE problem, the k -shortest paths are often selected to provision the primary substrat paths (i.e. primary virtual links).

In this section, we show that when the primary paths follow the shortest paths according to any static metric, the maximum number of backup paths is bounded even if the

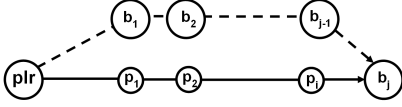


Fig. 2: Links forming primary and backup paths

primary bandwidth freed upon failure is infinite (i.e., the freed bandwidth is very larger than the protection bandwidth). This means that we cannot build a backup path with only links freeing bandwidth upon the failure of the protected risk.

Lemma 4.1: Any backup path protecting a primary shortest path (according to a strictly positive and static metric) against a link failure risk must include a link which doesn't free up any bandwidth. Formally:

$$\forall r \in E, \forall \pi \in Bp_r^{(s,t)}, \exists \lambda \in \pi : L_r^\lambda = 0$$

Proof: To free up bandwidth on a link λ upon failure of link $plr - p_1^2$, λ must belong to at least one shortest primary path crossing link $plr - p_1$ in one direction (from plr to p_1 or from p_1 to plr). In addition, link λ must be located on the downstream of link $plr - p_1$.

Let us define $Down_{(plr,p_1)}$ as a set of nodes located downstream to $plr \rightarrow p_1$ (in this direction) on the primary paths crossing plr and p_1 (see figure 2). Thus, only links interconnecting extremity nodes in $Down_{(plr,p_1)}$ can free up bandwidth upon failure of primary paths crossing link $plr \rightarrow p_1$. Here we prove that $Down_{(plr,p_1)} \cap Down_{(p_1,plr)} = \emptyset$.

Assume that there is a node b_i so that $b_i \in Down_{(plr,p_1)}$. This means that:

$$w(plr, b_i) = w(plr, p_1) + w(p_1, b_i) < w(p_1, b_i) \quad (5)$$

Where $w(plr, b_i)$ is the weight of any shortest path connecting node plr to node b_i and $w(p_1, b_i)$ is the weight of any shortest path connecting node p_1 to node b_i .

Actually, assume that $b_i \in Down_{(p_1,plr)}$. This means that:

$$w(p_1, b_i) = w(p_1, plr) + w(plr, b_i) < w(plr, b_i) \quad (6)$$

From formulas (5) and (6), we conclude that $b_i \in Down_{(plr,p_1)} \cap Down_{(p_1,plr)}$ leads to the following contradiction: $w(plr, b_i) < w(p_1, b_i) < w(plr, b_i)$. Thus : $Down_{(plr,p_1)} \cap Down_{(p_1,plr)} = \emptyset$

As the PLR node (source of the backup path) belongs to $Down_{(p_1,plr)}$ whereas the merge node (target of the backup path) is in $Down_{(plr,p_1)}$, no backup path connecting the PLR to the merge point could be established. In fact, any link connecting a node in $Down_{(p_1,plr)}$ to a node in $Down_{(plr,p_1)}$ cannot free up bandwidth. Indeed, the extremity nodes of a link freeing bandwidth must be in the same set $Down_{(plr,p_1)}$ or $Down_{(p_1,plr)}$. ■

Lemma 4.2: Any backup path protecting a primary shortest path (according to a strictly positive and static metric) against a

node failure risk must include a link which doesn't free up any bandwidth. Formally: $\forall r \in V, \forall \pi \in Bp_r^{(s,t)}, \exists \lambda \in \pi : L_r^\lambda = 0$

Proof: We prove the validity of lemma 4.2 by contradiction. In other words, if such a backup path exists, it must be shorter than the primary shortest path it protects.

Assume that there is one backup path $b = plr \rightarrow b_1 \rightarrow \dots \rightarrow b_j$ (see figure 2) composed of only links freeing up bandwidth after the failure of node p_1 (downstream to the PLR node plr). The backup path b protects a primary shortest sub-path $p = plr \rightarrow p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j$ according to the strictly positive and static metric \vec{w} (see Figure 2). Let us prove by induction on the k^{th} backup nodes that:

$$\forall k \leq j, \exists s \in Paths^{(plr,b_k)}, \forall \pi \in Paths^{(p_1,b_k)} : w(\pi) \geq w(p_1 \curvearrowright plr \rightarrow s \rightarrow b_k) \quad (7)$$

where $p_1 \curvearrowright plr$ is any shortest path from p_1 to plr .

$k = 1$

To free up bandwidth upon failure of node p_1 (see Figure 2), link $plr \rightarrow b_1$ must belong to at least one shortest primary path crossing node p_1 . In addition, link $plr \rightarrow b_1$ must be located on the downstream of node p_1 . This implies that:

$\exists s = plr \rightarrow b_1 \in Paths^{(plr,b_1)}$ so that:

$p_1 \curvearrowright plr \rightarrow s \rightarrow b_1$ is a shortest path.

This means that formula (7) is valid for $k = 1$.

Step $1 < k \leq j$

Assume that formula (7) is valid for $n = \overline{1, k-1}$ and prove that it is valid for $n = k$. To free up bandwidth upon failure of node p_1 , link $b_{k-1} \rightarrow b_k$ must belong to at least one shortest primary path crossing node p_1 . In addition, link $b_{k-1} \rightarrow b_k$ must be located on the downstream of node p_1 . This implies that:

$\exists s \in Paths^{(p_1,b_{k-1})}, \forall \pi \in Paths^{(p_1,b_k)}$:

$$w(\pi) \geq w(p_1 \rightarrow s \rightarrow b_{k-1} \rightarrow b_k)$$

As for $n = k-1$, we have:

$\exists s' \in Paths^{(plr,b_{k-1})}, \forall \pi' \in Paths^{(p_1,b_{k-1})} : w(\pi') \geq w(p_1 \curvearrowright plr \rightarrow s' \rightarrow b_{k-1})$, we deduce that (for $\pi' = p_1 \rightarrow s \rightarrow b_{k-1}$):

$$w(\pi) \geq w(p_1 \rightarrow s \rightarrow b_{k-1} \rightarrow b_k) = w(p_1 \rightarrow s \rightarrow b_{k-1}) + w(b_{k-1} \rightarrow b_k) \geq w(p_1 \curvearrowright plr \rightarrow s' \rightarrow b_{k-1}) + w(b_{k-1} \rightarrow b_k) = w(p_1 \curvearrowright plr \rightarrow s' \rightarrow b_{k-1} \rightarrow b_k)$$

Thus, path $p_1 \curvearrowright plr \rightarrow s'' \rightarrow b_k$ (with $s'' = s' \rightarrow b_{k-1}$ and $s'' \in Paths^{(plr,b_k)}$) is also a shortest path according to the metric \vec{w} . In other words, formula (7) is verified.

To prove the correctness of Lemma 4.2, we show now that formula (7) contradicts the shortness of the primary path $plr \rightarrow p_1 \rightarrow p_i \rightarrow b_j$.

We recall that the primary path $plr \rightarrow p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j$ corresponds to a shortest path. This implies that:

$$\forall \pi \in Paths^{(p_1,b_j)} : w(\pi) \geq w(plr \rightarrow p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j).$$

Thus, for any segment path $s \in Paths^{(plr,b_j)}$, we have:

$$w(plr \rightarrow s \rightarrow b_j) \geq w(plr \rightarrow p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j).$$

On the other hand, formula (7) implies for $k = j$ that:

$\exists s' \in Paths^{(plr,b_j)} \forall \pi' \in Paths^{(p_1,b_j)} : w(\pi') \geq w(p_1 \curvearrowright plr \rightarrow s' \rightarrow b_j) = w(p_1 \curvearrowright plr) + w(plr \rightarrow s' \rightarrow b_j) \geq w(p_1 \curvearrowright plr) + w(plr \rightarrow p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j) = w(p_1 \curvearrowright plr \rightarrow p_1) + w(p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j) > w(p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j)$. This leads to a contradiction since for $\pi' = p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j$ ($\pi' \in Paths^{(p_1,b_j)}$), we obtain: $w(\pi') = w(p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j) > w(p_1 \rightarrow \dots \rightarrow p_i \rightarrow b_j)$. Thus, formula (7) cannot be verified. In other words, any backup path protecting

²Even if we consider that the PLR plr is not adjacent the failed link $p_f - p_i$ (case of the global protection), we can easily prove the correctness of Lemma 4.1.

against a node failure risk must utilize at least one link which cannot free up bandwidth upon that node failure. ■

Proposition 4.3: Every backup path should cross a link that cannot free up bandwidth after the failure of a protected risk.

Proof: Any backup path protects at least against the failure of a link located on the downstream of the PLR. From Lemma 4.1, we conclude that every backup path should cross a link that don't free up bandwidth after a failure of a protected link. ■

Theorem 4.4: Consider that any path requires at least one unit of bandwidth. The number of backup paths that can be build in a network $G = (V, E, \vec{w}, \vec{C})$ is bounded if $|E|$ and $(C^\lambda)_{\forall \lambda \in E}$ are bounded.

Proof: For the proof, we first show that for any link, the number of backup paths protecting against its failure is bounded. From Lemma 4.1, we know that any backup path protecting against any link failure risk r_l should cross at least one link λ that cannot free up bandwidth after the failure of r_l . From formulas (3) and (4), we have:

$$\delta_{r_l}^\lambda - L_{r_l}^\lambda \leq \max_r (\delta_r^\lambda - L_r^\lambda, 0) \leq C^\lambda$$

As the protection cost $\delta_{r_l}^\lambda$ is higher than the number of backup paths protecting against the failure r_l and crossing link λ (since any backup path requires at least one unit of bandwidth), we deduce that this number of backup paths is bounded by $\lfloor C^\lambda \rfloor$. Because the number of links freeing up some bandwidth after the failure of r_l is lower than $|E|$, we conclude that the number of backup paths protecting against the link failure risk r_l is bounded by $\sum_{\lambda \in E} \lfloor C^\lambda \rfloor \leq |E| \times \lfloor \max_{\lambda \in E} (C^\lambda) \rfloor$.

Similarly, we deduce that the maximum number of backup paths that can be built in the network is bounded by $|E|^2 \times \lfloor \max_{\lambda \in E} (C^\lambda) \rfloor$ since the number of distinct link failure risks is lower or equal to $|E|$. ■

Interpretation:

- With both the global and restrained bandwidth sharing strategies, the number of backup paths is bounded when the protection capacities (or the link capacities) are bounded. As any backup path should cross at least one link that don't free up bandwidth, the use of the global bandwidth sharing strategy instead of the restrained bandwidth sharing strategy could not avoid network redimensioning over the long term.
- When a great amount of traffic is not protected (for instance, best-effort traffic), the freed bandwidth on some links upon failure could be high. Even in this case, the maximum number of backup paths is bounded specifically by the capacity of links that cannot free up bandwidth.

Whereas the maximum number of backup paths depends on all the network links with the restrained bandwidth sharing strategy, this number depends more on the links that cannot free up bandwidth with the global bandwidth sharing strategy. In the next section, we compare by simulations these two bandwidth sharing strategies to quantify the gain in performances due to the exploitation of the freed bandwidth.

V. SIMULATION AND PERFORMANCE ANALYSIS

A. Simulation model

In order to quantify the gain in performances due to the use of the global bandwidth sharing instead of the restrained bandwidth sharing, we compared the two bandwidth sharing strategies by simulations. In our experiments, we used two well known topologies of network: Long Haul and Cost 239. The first network topology is composed of 28 nodes and 45 bidirectional links. The protection capacities of links are equal to 200 units in each direction except for 6 links located on the northeast border which have a protection capacity of 600 units. This network topology is relatively wide and presents a mean connectivity degree of 3.21. The second network topology is composed of 11 nodes and 26 bidirectional links. It is small and strongly connected since its mean connectivity degree is equal to 4.73. All the links of this network have the same protection capacity that is equal to 200 units in each direction.

To take into account the two possible models of bandwidth allocation (unidirectional bandwidth allocation and bidirectional bandwidth allocation), we considered two test scenarios: unidirectional allocation-based scenario (*UAS*) and bidirectional allocation-based scenario (*BAS*). In the first test scenario, the unidirectional bandwidth allocation method is applied for bandwidth allocation. It means that two protection pools are associated to each bidirectional link. In the second test scenario, the bidirectional bandwidth allocation method is applied for bandwidth allocation. It means that only one protection pool is associated to each bidirectional link.

In our simulations, we generated sequentially 1000 demands of protected path establishment asking for bandwidth quantities uniformly distributed between 1 and 10 units. Each demand is composed of one primary path establishment request that is always satisfied (i.e., we assumed that the primary pool capacities of links are sufficient to satisfy all the requests of primary path establishment) and several requests of backup path establishment allowing local protection of the built primary path. The source and target nodes of each primary path are selected uniformly among the set of network nodes. For the computation of primary paths, we applied the shortest path first (SPF) algorithm that optimizes the number of hops whereas we used the constrained shortest path first (CSPF) algorithm for the computation of backup paths.

Two criteria are selected to compare the global and restrained resource sharing strategies: rate of backup path rejection (*BPR*) and rate of protection bandwidth utilization (*PBwU*). The first criterion *BPR* is computed for different network loads. It determines the ratio of backup paths that are rejected because of the lack of protection bandwidth on the network links. It corresponds to the (instantaneous) ratio between the number of backup path requests that are rejected and the total number of backup paths required to protect entirely the last 50 primary paths. Formally, it is determined as follows:

$$BPR = \frac{\# \text{rejected protection requests}}{\# \text{protection requests}}$$

The second criterion *PBwU* determines and measures the efficiency of bandwidth sharing. It corresponds to the ratio between the sum of all the protection costs and the amount of the bandwidth allocated in the network for the protection. Formally, it is computed as follows:

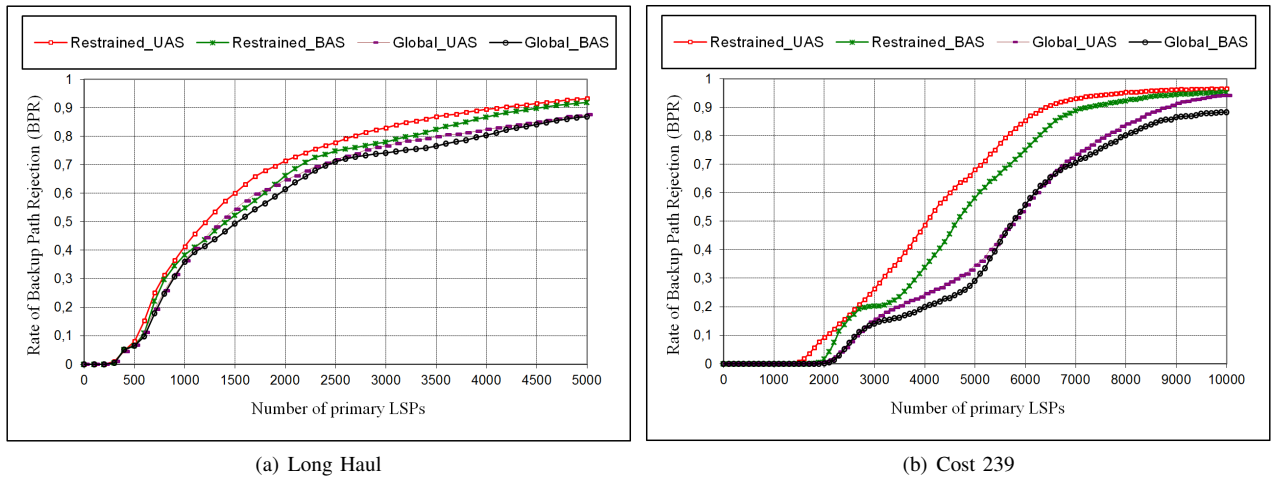


Fig. 3: Evolution of the mean rate of backup path rejection

$$PBwU = \sum_{(\lambda, r) \in E \times (V \cup E)} \delta_r^\lambda / \sum_{\lambda \in E} R^\lambda.$$

For each test scenario (*UAS* and *BAS*) and at each establishment of 50 primary paths, the two metrics *BPR* and *PBwU* are computed for the two compared strategies. We note that our results correspond to mean values over 1000 experiments.

B. Results and Analysis

Figure 3 shows the evolution of the *instantaneous* rate of backup path rejection (BPR) as a function of the number of primary paths setup in the network for the unidirectional and bidirectional bandwidth allocations.

As expected, we observe in Figure 3 that the bidirectional bandwidth allocation method is slightly better than the unidirectional bandwidth allocation method. Indeed, Figure 3 clearly shows that the global and restrained bandwidth sharing strategies using the bidirectional bandwidth allocation method have respectively smaller rejection rates than the global and restrained bandwidth sharing strategies using the unidirectional bandwidth allocation method. These observations can be explained by the distribution of the protection costs on links (especially on opposite links) which is heterogeneous.

In addition, figure 3 shows that the difference in BPR between the compared strategies is small and even imperceptible sometimes. For instance, in Longhaul network topology, the difference in instantaneous BPR does not exceed 8 %, even for high loads of traffic (a large number of primary paths) where the instantaneous rejection rate of backup path is high and inefficient. For usual instantaneous rejection rates that should be lower than 10 %, the difference between the compared strategies is often not perceptible.

Obviously, the difference in the backup path rejection is directly related to the amount and distribution of the freed bandwidth on links. Since the freed bandwidth is statically high on the links close to PLRs and generally low on the links located far from PLRs, the difference in backup path rejection rates of the compared strategies is slightly higher in COST 239 network topology than in Longhaul network topology.

Indeed, the links are closer to the PLRs in COST 239 since it is more homogeneous and it has a larger connectivity degree than Longhaul.

In addition of the previous observations, we note that even for high freed bandwidth values, the rates of backup path rejection increase with the augmentation of the traffic load and they converge to the saturation state where almost all the new protection requests are rejected. This corroborates our theoretical results which announces the existence of an upper bound for the number of backup paths that can be established in the network even with unlimited resources.

With regards to the second metric (bandwidth sharing utilization), Figure 4 shows that both the global and restrained bandwidth sharing strategies have similar bandwidth utilization rates for small and usual backup path rejection rates. For instance, the difference in bandwidth sharing utilization for the compared strategies is very small in Longhaul network (see Figure 4 (a)) when the number of primary paths is lower than 1000 (all the backup path rejection rates are lower than 0.3) whereas the difference is imperceptible in COST 239 network (see Figure 4 (b)) when the number of primary paths is lower than 3000 (all the backup path rejection rates are lower than the usual value 0.15). For high traffic loads, Figure 4 shows that the global bandwidth sharing strategy is better than the restrained bandwidth sharing strategy. This is essentially due to the amount of freed bandwidth which increases with the augmentation of the rejection rate of backup paths. Indeed, whereas the protection bandwidth is completely independent of the freed bandwidth variation when the restrained bandwidth sharing strategy is applied, it decreases with the augmentation of the freed bandwidth when we apply the global bandwidth sharing strategy.

To summarize, these simulations show that the difference in performances between the global and restrained bandwidth sharing strategies is almost imperceptible for low traffic loads where the rejection rate of backup path is small and usual. For high traffic loads where the rejection rate of backup paths is high, the global bandwidth sharing strategy is slightly better than the restrained bandwidth sharing strategy. In addition to

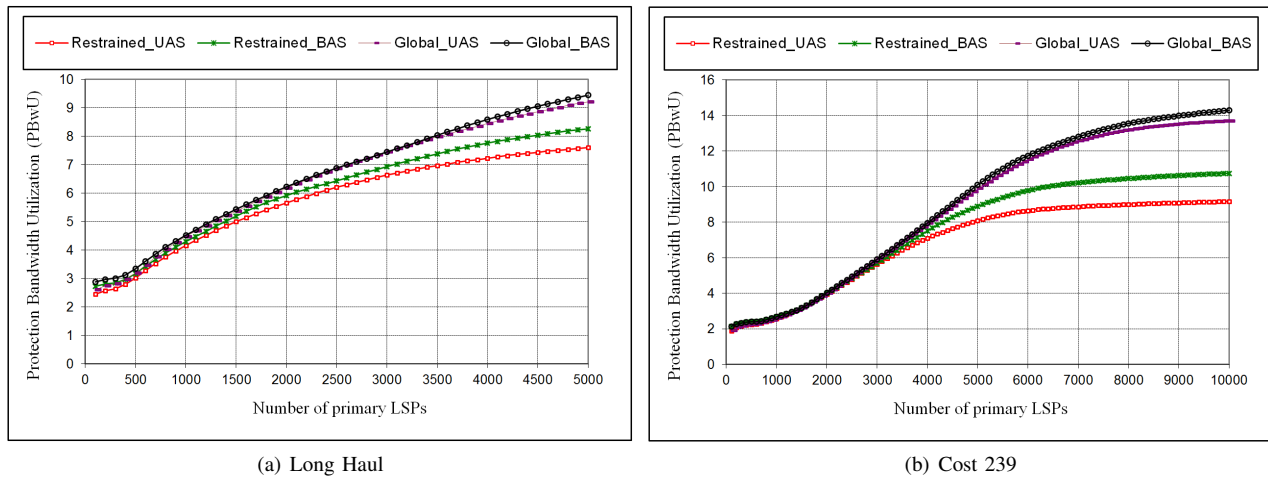


Fig. 4: Evolution of the mean rate of protection bandwidth utilization

the precedent remarks, our simulations comfort our theoretical results (see Thorem 4.4) and show clearly that the number of backup paths is always bounded even if the freed bandwidth is unlimited on the links that are capable to free up bandwidth.

VI. CONCLUSION

In this article, we presented two known strategies of resource (bandwidth) sharing: restrained bandwidth sharing and global bandwidth sharing. The first strategy limits the bandwidth sharing to the backup paths that protect against different failure risks whereas the second strategy extends the bandwidth sharing to the primary and backup paths that could not be active at the same time.

To measure the gain obtained by the extension of the bandwidth sharing to the primary and backup paths, we firstly showed theoretically that the bandwidth sharing between the primary and backup paths can never be applied on some backup links when the primary paths correspond to the shortest ones (according to a static metric). Thus, the maximum number of backup paths is limited and bounded by the protection capacities of links. Secondly, to quantify the improvement due the bandwidth sharing between the primary and backup paths, we showed by simulations that the gain in performances (backup paths rejection and bandwidth utilization) is often imperceptible, particularly for low traffic loads where the rejection rate of backup paths is small and usual. For high traffic loads where the rejection rates are high, the global bandwidth sharing strategy is slightly better than the restrained bandwidth sharing strategy, especially in strongly connected networks.

As a result, the global bandwidth sharing strategy cannot be a long term solution for supporting bandwidth-intensive applications especially since the global bandwidth sharing strategy induces an overcost. Indeed, in return of the slight performance improvements the global bandwidth sharing allows, we note the complication of path computation and the necessity to maintain larger information. For instance, additional computations should be done with the global bandwidth sharing strategy to determine the amount of freed bandwidth after each establishment or liberation of a primary path.

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