Survivability Analysis on Non-Triconnected Optical Networks under Dual-Link Failures

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***Abstract*—Survivability of optical networks is considered among the most critical problems that telecommunications operators need to solve at a reasonable cost. Survivability can be enhanced by increasing the amount of network links and its spare capacity, nevertheless this deploys more resources on the network that will be used only under failure scenarios. In other words, these spare resources do not generate any direct profit to network operators as they are reserved to route only disrupted traffic. In particular, the case of dual link failures on fiber optic cables (i.e., fiber cuts) has recently received much attention as repairing these cables typically requires much time, which then increases the probability of a second failure on another link of the network. In this context, survivability schemes can be used to recover the network from a dual link failure scenario. In this work, we analyze the case of protection and restoration schemes, which are two well-known recovery strategies. The former is simpler to implement as it considers a fixed set of backup paths for all failure scenarios; however, it cannot take into account the spare capacity released by disrupted connections. Instead, the latter computes the best recovery path considering not only the spare capacity but also the released one due to failures. Achieving 100% survivability (i.e., recovery from all possible dual link failures) requires a triconnected network, where three disjoint paths for each connection are required. Since these networks can become extremely expensive since they can require a huge number of network links (i.e., fibers connections), a more realistic case of non-triconnected networks is assumed. In these networks, full network recovery is not be feasible, but achieving the maximum possible survivability is desired. Spare capacity can then be allocated to existing network links, which represents the actual cost of the survivability. We propose optimization models that take into account these different recovery strategies, and demonstrate that restoration has the potential to provide a much better recovery capability with almost the same amount of spare capacity required in protection schemes.**

I. Introduction

Survivability is one of the most important aspects of optical transport networks as it enables to withstand and recover from failures which otherwise can disrupt telecommunications services. However, survivability can only be obtained by allocating spare capacity on network links. This spare capacity is used to reroute interrupted services due to failures. Since spare capacity has a direct impact on the actual cost of the network, operators make use of optimization models to design their networks in order to minimize this capacity while maximizing network survivability.

Research in optical transport networks survivability has traditionally been focused on single-link failures [1], in particular on the case of optical link failures (i.e. fiber cuts). Nevertheless typical repair times for fiber cuts are large, then the probability of a dual fiber cut scenario in large transport networks may become relevant. In the past several works have also considered dual link failures [2], [3], [4]. Empirical observations can be found in [5]. Authors in [6] studied the impact of dual failures in networks planned to protect single failures. In [7] the dual failure restorability of networks designed for single failure survivability problem is addressed using shared backup paths. Dual-link failures restorability using p-cycle is studied in [8],[9]. An Hybrid Protection/Restoration approach is studied in [10] for WDM networks reducing the spare capacity compared with a full protection scheme. In [4],[11] the authors studied the spare capacity allocation problem using shared backup paths on triconnected networks and using partially-disjoint backup paths on non-triconnected networks.

Survivability of 100% possible dual-link failure scenarios can result in huge costs as it requires triconnected optical networks [4], where each service can be established through either one of three completely disjoint paths. The improvement of survivability by means of triconnected networks involves increasing the number of network links. These links require the deployment of fiber optic cables which can be extremely expensive. Commercial optical transport networks are not typically triconnected because of this reason. Instead, network operators prefer to increase the spare capacity on already deployed fibers as it is much cheaper. Indeed, network capacity is typically enlarged today by upgrading terminal equipment on the existing fiber link. In this paper, we investigate, model and analyze the optimization problem of minimizing spare capacity in non-triconnected optical networks. We address this problem from the point of view of two different survivability strategies: protection and restoration.

Protection schemes refer to the fact that recovery from link failures is based on preset backup paths. Upon failure detection, a terminal equipment can use these backup paths to re-establish the lost connection. Some spare capacity is thus reserved for these paths. Authors in [4] have studied the problem of finding two backup paths per connection that minimize the total spare capacity. In this scenario, a set of three link-disjoint paths per connection must exist, namely a working path, a primary backup path and a secondary backup path. If so, all connections can survive to any dual link failure scenario as it is guaranteed that at least one out of the three paths will always be available. However, in non-triconnected networks, three disjoint paths per connection may not exist,

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then partially disjoint paths can be found for the primary and secondary backup paths [11]. These connections will not survive to the dual-link failure scenarios that affect the working path as well as the shared link on the backup paths. Even if 100% recovery is not possible in these scenarios, the main goal still is to allocate the minimum amount of spare capacity that provides the maximum recovery capability.

Even if protection schemes are widely used due to their simplicity, they tend to reserve a lot of spare capacity to guarantee survivability on all possible failure scenarios. Besides, the working capacity, which is allocated for the original working path, cannot be used to re-establish connections. Restoration schemes do not define a fixed set of backup paths as protection does, instead a restoration path is computed over each failed scenario. This path can consider not only the available spare capacity but also the working one that has been released by the lost connections. As a result, restoration can require allocating less spare capacity than protection schemes. Since working capacity is released, restoration can also provide a better recovery capability with respect to protection schemes.

Historically the main disadvantage of restoration schemes has been that they expend lot of time in the path discovery process since this process is done in a distributed fashion. But in the last years the concept of software defined optical networks (SDON) was introduced [12]. Software defined optical networks is still an open research field and its implementations are still under discussion. Nevertheless is expected that software defined networks will allow applications to control network resources or information across different technology domains. This will enable fast restoration and centralized restoration. In [13] authors propose a fast restoration scheme based on SDON. In this work we investigate how a centralized restoration scheme can help in dual-link failures survivability.

In this paper, we evaluate protection and restoration strategies under single/dual link failure scenarios. Including centralized and distributed restoration schemes. In Section II we discuss their behavior in non-triconnected networks. In Section III the well-known Spare Capacity Allocation (SCA) problem [14],[4] is defined for these schemes. Optimal solutions to the problem are obtained by means of Integer Linear Programming (ILP) models described in Section IV . Finally in Section V we show results for three different non-triconnected networks. This results show that restoration schemes can provide a much better recovery capability with almost the same spare capacity.

II. Survivability Schemes

The optical networking community uses the term survivability to mean link node-level fault tolerance [15]. Fault tolerance relies on redundancy to compensate random uncorrelated failure of components. Protection schemes make use of preplaned and reserved resources to re-route traffic in presence of link failures. While restoration schemes make use of the spare capacity to re-route services after the failure has occurred.

A. Protection

If only single-link failures are being taken into account, traditional schemes with single backup path, such as dedicated protection (1+1) and shared protection (1:1), can be used. This schemes need fully bi-connected networks to provide 100% single-link failures tolerance. Nevertheless this schemes can't provide tolerance to all possible dual-link failures. If protection against dual-link failures is required, two backup paths are mandatory. This protection schemes can only provide 100% dual-link failures tolerance in triconnected networks. In non-triconnected networks, three disjoint paths may not exist, so partially disjoint paths must be used for dual-link failures protection schemes.

1) 1+1 Protection: A primary backup path is allocated for each service. The working path and the backup path must be link-disjoint. This protection scheme can be used in biconnected networks in order to provide single-link failure survivability.

2) 1:1 Protection: A primary backup path is reserved for each service, if the working paths of two different flows are disjoint then the capacity of the protection paths can be shared. This scheme can be used in biconnected networks in order to provide single-link failure survivability.

3) 1+1+1 Protection: In this scheme, a primary and a secondary backup paths are reserved for each service, where dedicated capacity is allocated for each path. These backup paths and the working path must be mutually link-disjoint to provide 100% dual-link failures survivability. In non-triconnected networks, this scheme can be used by means of partially disjoint backup paths, but 100% survivability is not guaranteed.

4) 1+1:1 Protection: This scheme also requires reserving a primary and a secondary backup path for each service. If these paths can be mutually link-disjoint (triconnected network), then 100% dual-link failures survivability is guaranteed. Instead of allocating dedicated capacity for all backup paths as in 1+1+1, spare capacity can be shared for secondary backup paths. This is feasible whenever two services have mutually link-disjoint working and primary paths.

5) 1:1:1 Protection: Further spare capacity reduction can be potentially achieved by sharing capacity among all primary and secondary backup paths.These capacities can be shared between two primary or secondary backup paths if they are never used simultaneously. Still a primary and a secondary backup paths are reserved for each service, these two paths and the working path must be mutually link-disjoint; otherwise, 100% dual-link failures survivability is not possible.

B. Restoration

Restoration schemes deal with link failures in a reactive way by searching for a restoration path once the failure has occurred. Nowadays restoration is done in a distributed fashion. This means that the path discovery and configuration can take several time to be completed. Also, it can happen that there is no enough capacity left for the restoration. An alternative that can deal with these limitations is a centralized

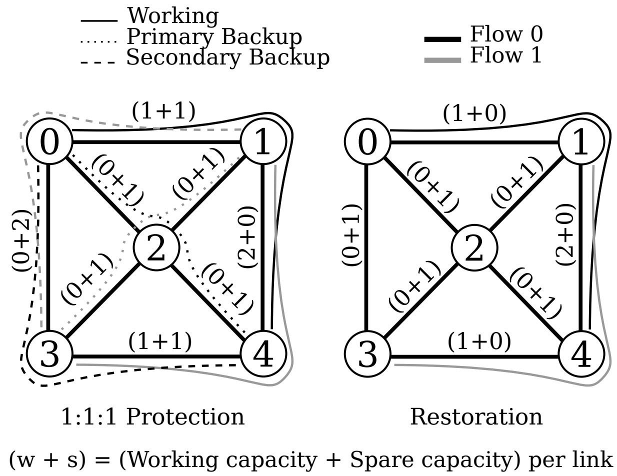

Fig. 1. Shared protection vs. restoration

restoration scheme. This kind of centralized restoration scheme can become possible in the near future as software defined optical networks are evolving quickly. Spare capacity can be allocated in order to guarantee that enough capacity is available for restoration in every single/dual link failure scenario. In triconnected networks all possible dual-link failures can be restored, while in non-triconnected networks only some scenarios can be restored. Restoration schemes allow full capacity sharing, meaning that two paths can share their capacity if there is no scenario in which their are both active.

Whenever a working path is interrupted, its capacity can be released. In protection schemes this capacity is never shared because working paths and backup paths must be disjoint. In restoration schemes this capacity can be fully shared since a restoration path is always independent of any other path.

In Fig. 1 we show an example of a triconnected network with two connection flows (services), Flow 0 and Flow 1, each one demanding one unit of traffic. We define paths as a sequence of node indexes n_i given by $< n_1, n_2, ..., n_p >$, where n_0 is the index of the source node of the flow, n_p is the index of destination node of the flow, and $n_i, 1 > i > p$ are the indexes of intermediate nodes. Flow 0 has a working path given by $< 0, 1, 4 >$ (continuous black line) and Flow 1 has a working path given by $< 1, 4, 3 >$ (continuous gray line). For 1:1:1 protection scheme (left case), a primary and a secondary backup paths are defined for each flow. Flow 0 has $< 0, 2, 4 >$ as primary backup and $< 0, 3, 4 >$ as secondary backup path, while Flow 1 has $< 1, 2, 3 >$ and $< 1, 0, 3 >$ as primary and secondary backup paths, respectively. For the restoration scenario (right case), no backup paths are defined but spare capacity is allocated for restoration paths. Allocated capacity is shown on each link as $w + s$, where w refers to working capacity, and s, to spare capacity. In 1:1:1 protection, only backup paths can share spare capacity but in restoration the working and the spare capacity is shared enabling further capacity saving.

Fig. 2 shows how the working capacity can be shared in a restoration scheme. When links $(2, 4)$ and $(1, 4)$ fail, both flows (services) must be restored. The working capacity in link $(3, 4)$ is released and can be used by the restoration paths. The same happens when link $(1, 2)$ and $(1, 4)$ fail, the working capacity in link $(0, 1)$ is used by the restoration path of Flow 1.

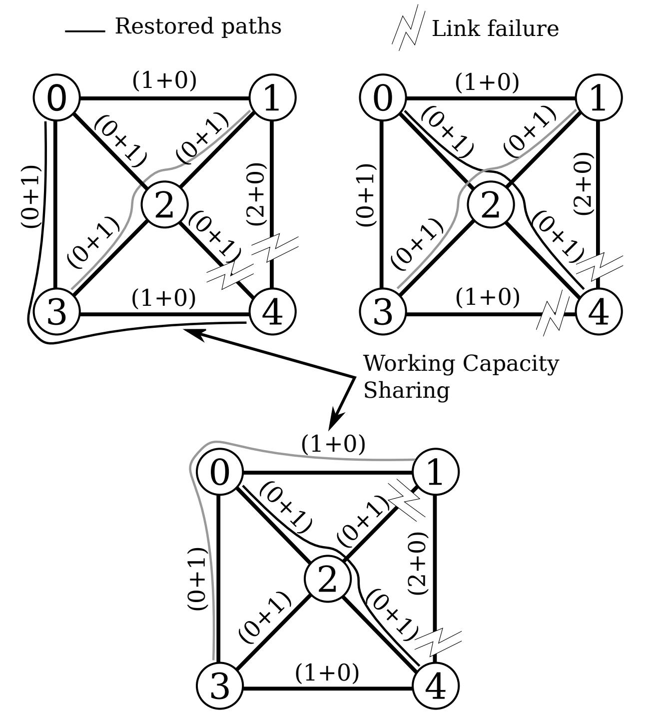

Fig. 2. Working capacity sharing in restorations schemes

Survivability of all dual-link failure scenarios is not possible on non-triconnected networks. We define a recovery index R that compares the number of dual-link failure scenarios that the network can survive with respect to the total dual failure scenarios. For a network with M links the total single/dual link failure scenarios are $\binom{M}{2} + M$, then

$$R = \frac{survivable \quad scenarios}{\binom{M}{2} + M} \times 100$$

In non-triconnected networks, restoration schemes can achieve better performance than protection schemes in terms of the recovery index R.

In Fig. 3 we show the case of a biconnected network with only one flow (service). For 1:1:1 protection, seven spare capacity units are needed and the 96,66% of the single/dual link failure scenarios are covered. If a shared restoration scheme is being used, then eight spare capacity slots are needed but the 99,16% of the single/dual link failure scenarios are covered. It is worth noticing that even if we add more spare capacity on the links for the 1:1:1 protection, the recovery capability R can't be increased. Instead, a restoration strategy enables allocating more spare capacity (i.e., one unit more) in order to increase the recovery index.

1) Centralized versus Distributed Restoration: Restoration schemes select a route for each disrupted flow after the disrup-

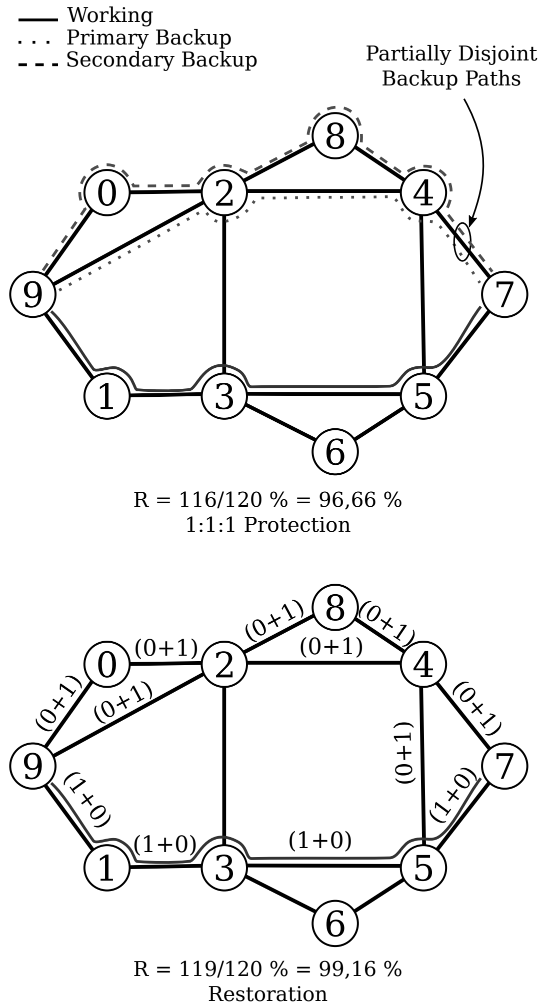

Fig. 3. Survivability in biconnected network

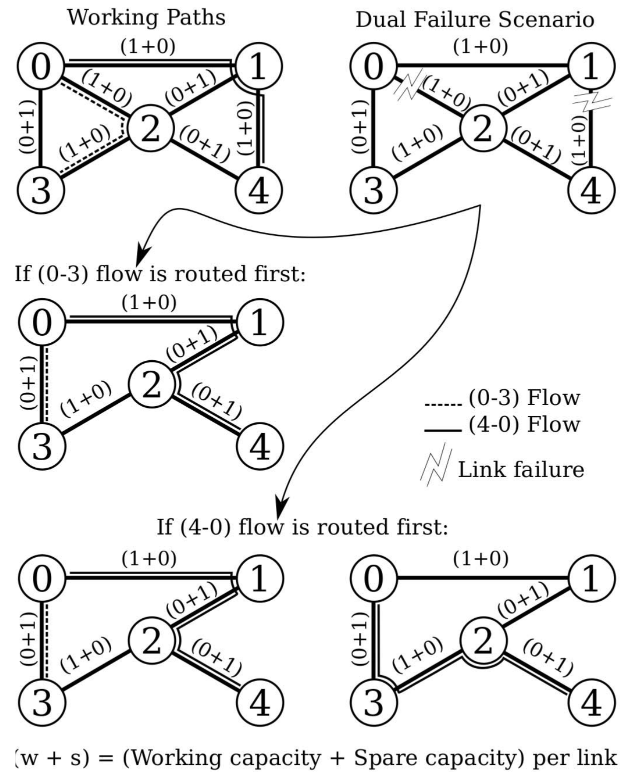

Fig. 4. Blocking on distributed restoration scheme

tion has occurred. This re-routing can be made by a centralized manager or in a distributed fashion. In the centralized scheme, the decision is made taking into account all the possible scenarios. In a distributed scheme, an equipment may make a decision upon a disruptive event that affects the availability of spare capacity to route other flows (services). Blocking can happen and depends on which equipment routes first. In Figure 4 a five node graph is shown, with two flows (services), one from node 0 to node 3 with its working path $< 0, 2, 3 >$ and the second flow from node 4 to node 0 with working path $< 4, 1, 0 >$. If at any time links $(0, 2)$ and $(1, 4)$ fail, the two flows must be restored. In a distributed scheme, it can happen that flow from 0 to 3 restores first through the shortest path from 0 to 3. However, if flow from 4 to 0 restores first there are two different shortest paths. Then, if node 4 chooses $< 4, 2, 1, 0 >$ there is no blocking but if node 4 chooses path $< 4, 2, 3, 0 >$ for the restoration then the flow from node 0 to node 3 will be blocked. Note that node 4 has no way to know if the path selected is globally optimal. In a centralized scheme, the central routing manager can choose both routes in an optimal way in order to avoid blocking.

III. SCA PROBLEM STATEMENT

The Spare Capacity Allocation (SCA) problem consists of finding the minimum spare capacity needed to guarantee network survivability. As discussed before, 100% survivability to dual-link failures can only be achieved in triconnected networks. For the case of non-triconnected networks the problem can be described as finding the minimum spare capacity that maximize the single/dual link failures survivability. Since we will consider networks that are not triconnected, we will use the the recovery index R as a to compare the performance of the different schemes.

An optical network can be represented as an undirected graph $G = \{V, E\}$ of N nodes, M links and K flows (services). Each flow k, $1 \leq k \leq K$ has its source/destination node s^k, d^k and a capacity demand C^k. Each flow k has a working path given by P^k_{ij}, where $P^k_{ij} = 1$ if the working path of flow k uses link $(i, j) \in E$, and $P_{ij} = 0$ otherwise. As each single/dual-link failure leads to a new topology, each scenario can be modeled as a new graph based on G where the failed links are removed from E. This results in a multi-graph structure $\mathbf{G} = \{G_g\} = \{V_g, E_g\}$ where each subgraph G_g has a node set $V_g = V$, and link set E_g. This is illustrated in Fig. 5.

In a given subgraph G_g, the working path of each flow k may be interrupted. This is represented by the P^k_g coefficients, where $P^k_g = 1$ if the flow k can be routed over its working path in subgraph G_g and $P^k_g = 0$ otherwise. Moreover, a flow must use the working path whenever it is available, so a $P^k_g = 1$

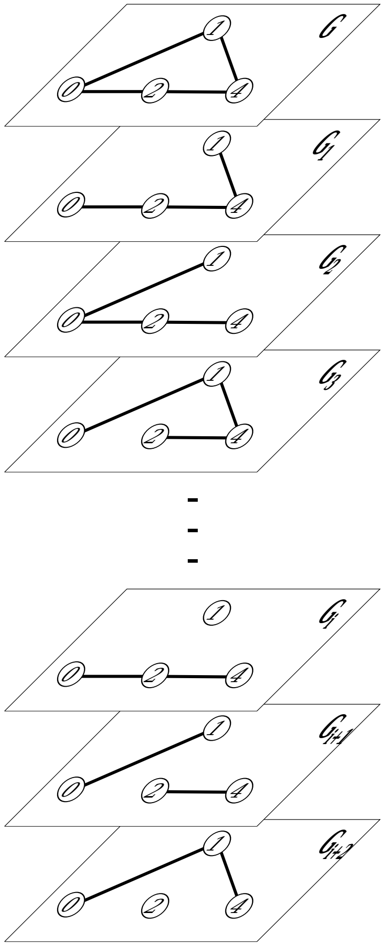

Fig. 5. Multi-graph representation

also indicates that the working path of flow k must be used in subgraph G_g.

Since this model must take into account non-tricconected networks, it is possible that in a particular subgraph G_g no path for a flow k is available. In that case, there is no way to route the flow in that subgraph and no capacity allocation is required. We consider $\mathbf{K_g}$ as the set of all flows k that have path availability in subgraph G_g. If k is not present in $\mathbf{K_g}$, then that flow does not require capacity on subgraph G_g.

The total capacity allocated on link (i, j) for subgraph G_g is referred as c_{gij}, and it depends on all flows routed through (i, j) for subgraph G_g and their capacity demands C^k. The resulting capacity allocated on link (i, j) for the graph G is referred as c_{ij}, this capacity has to take into account the link capacities required by all subgraphs. Note that two paths routed on the same subgraph cannot share capacity, but two paths routed on different subgraphs can fully share capacity, then $c_{ij} \geq c_{gij}$. In this context, the working capacity allocated on link (i, j) is $w_{ij} = \sum_{k=1}^{K} C^k P_{ij}^k$, while the spare capacity allocated in link (i, j) is $s_{ij} = c_{ij} - w_{ij}$.

The total spare capacity s allocated on the network is the sum of all the spare capacities allocated on each link, $s = \sum^{(i,j)\in E} s_{ij}$. The main goal of the SCA problem is then to minimize the total spare capacity s while maximizing the number of survived scenarios.

In restoration scheme the spare capacity allocated must guarantee that for each G_g the flows in $\mathbf{K_g}$ are satisfied. In protection schemes the spare capacity allocated is for backup paths, and the sharing can only be achieved if two paths are never used in the same subgraph G_g simultaneously. Further constraints are introduced in next section for protection backup paths, nevertheless all the formulation provided in this section is used for protection schemes too.

IV. Survivability SCA Models

In this section we describe the different survivability models for the SCA problem. We consider the case of restoration mainly, and compare with the cases of shared protection (1:1:1) and dedicated protection (1+1+1). These models require some preprocessing tasks that enable to better formulate these models as Integer Linear Programing formulations (ILP).

A. Preprocessing

Given the network topology represented as the graph $G = (V, E)$ with N nodes, M links and a working path wp^k and a capacity demand C^k for each flow k with $1 \leq k \leq K$, we first generate all the required coefficients by the model. The working path represented by $wp^k =< n_1, n_2, ..., n_p >$ must be mapped to the coefficients P_{ij}^k. If the sequence n_i, n_j exists in the path wp^k then $P_{ij}^k = 1$ and $P_{ij}^k = 0$ otherwise. From each working path $wp^k =< n_1, n_2, ..., n_p >$ source node s^k and destination node d^k must be mapped, $s^k = n_1$, $d^k = n_p$.

As described earlier, $\mathbf{G}$ is the set of all single/dual link failure scenarios of G, $\mathbf{G} = \{G_g\}$ where each $G_g = (V_g, E_g)$ is a graph with the same node set $V_g = V$ and with a link set E_g that is a copy of E but with one/two links subtracted from it. The number of subgraphs G_g is $\binom{M}{2} + M$. Once the $\mathbf{G}$ set is computed the P_g^k coefficients can be generated. For each subgraph G_g the working paths of the K flows must be evaluated, if working path wp^k is available on subgraph G_g then $P_g^k = 1$, and $P_g^k = 0$ otherwise, with $1 \leq k \leq K$. Finally, for each flow k path availability must be tested for each subgraph G_g. This is, if at least one path from s^k to d^k exists in subgraph G_g, then $k \in K_g$ and if no path can be found then $k \notin K_g$.

B. Distributed Restoration Model

Distributed restoration spare capacity problem can't take advantage of the multi-graph optimization. The reason for this is that no global metric is used in the path discovery process. The route discovery is triggered in each source node once the failure has occurred and is solved using some kind of shortest path algorithm. In order to model the SCA problem for the distributed restoration scheme we developed an computational method. This method computes the minimum spare capacity that guarantee enough capacity for restoration in each scenario. For each subgraph G_g a shortest path algorithm is called for each interrupted flow (service) k. Spare capacity is allocated for each path. Capacity can be shared between paths used in different subgraphs, but capacity can never be shared between paths that are used simultaneously in a specific subgraph.

C. Centralized Restoration ILP Model

First, we introduce the ILP model for the restoration scheme. The objective is given by Eq. 1 of the model, which aims at minimizing the total spare capacity s along all the network. This value take into account all the spare capacity allocated on each link to guarantee the best achievable recovery performance R. Constraints can be split into: 1) flow constraints Eq.2, Eq.3, Eq.4, Eq.5, and 2) capacity constraints Eq.6, Eq.7, Eq.8, Eq.9.

1) Flow constraints: The flow variables x^k_{gij} represent the route of flow k in subgraph G_g, where $x^k_{gij} = 1$ implies that the flow k goes through link (i, j) in subgraph G_g. Constraint Eq. 2 ensures that the flow continuity for each flow $k \in \mathbf{K_g}$ from s^k to d^k in subgraph G_g. This continuity constraint is only present if k is in $\mathbf{K_g}$, so the flow must be routed only if at least one path exists from s^k to d^k. Constraint Eq. 3 avoids loops in the flows, that means a link can never be used twice for one flow.

The working paths must be used whenever they are available. Constraint Eq. 4 forces flow variables to $x^k_{gij} = 1$ if the working path of flow k is available in G_g and link (i, j) is part of that path. $P^k_g = 1$ is one only when working path of flow k is available on subgraph G_g and P^k_{ij} is one if link (i, j) is part of the working path of flow k. If a link (i, j) is not present (i.e., fiber cut) in subgraph G_g, it means that $(i, j) \notin E_g$ and no flow can be routed through it. Constraint Eq. 5 force flow variables that cant be used to zero.

2) Capacity constraints: The total capacity needed on link (i, j) in subgraph G_g is given by c_{gij}, which accounts for both the working and spare capacity. This variable is undirected, so all the capacities allocated in both directions $(i, j), (j, i)$ of all flows must be added. Constraint Eq. 6 computes total capacity allocated per link on each subgraph G_g.

Since the restoration scheme allows capacity sharing between paths that are in different subgraphs, then the total capacity allocation per link is the largest allocation along all the subgraphs, Eq. 7. This total capacity per link c_{ij} includes working capacity and spare capacity, constraint Eq. 8 represents this relation.

Finally, the total spare capacity is the sum of all the spare capacities allocated per link, Eq.9.

TABLE I
INPUT DATA

$N, M, K, \|\mathbf{G}\|$	Number of nodes,links, flows, graphs
$\mathbf{G} = \{G_g\} = \{(V_g, E_g)\}$	Double failure graphs set
C^k	Capacity demands
s^k, d^k	source/destination nodes of flow k
P^k_{ij}	Working paths link coefficients
P^k_g	Working paths availability coefficients
$\mathbf{K_g}$	Path availability for each flow k in graph g

TABLE II
VARIABLES

x^k_{gij}	Binary, is set iff edge (i, j) is used by flow k in subgraph G_g
c_{gij}	Integer, allocated capacity in edge (i, j) in subgraph G_g
c_{ij}	Integer, total allocated capacity in edge (i, j)
s_{ij}	Integer, total allocated spare capacity in edge (i, j)
s	Integer, total allocated spare capacity

Minimize:

$$s \tag{1}$$

Subject to:

$$\sum_{j=1}^{M} x^k_{gij} - \sum_{j=1}^{M} x^k_{gji} = \begin{cases} 1 & \text{if } i = s^k \\ -1 & \text{if } i = d^k \\ 0 & \text{other} \end{cases} \qquad \forall g, i, k \in K_g \tag{2}$$

$$x^k_{gij} + x^k_{gji} \leq 1 \qquad \forall g, k, i, j \tag{3}$$

$$x^k_{gij} \geq P^k_{ij} P^k_g \qquad \forall g, i, j, k \tag{4}$$

$$x^k_{gij} = 0 \qquad \forall (i, j) | (i, j) \notin E_g \tag{5}$$

$$c_{gij} = \sum_{k=1}^{K} C^k (x^k_{gij} + x^k_{gji}) \qquad \forall g, i, j \tag{6}$$

$$c_{ij} \geq c_{gij} \qquad \forall g, i, j \tag{7}$$

$$s_{ij} = c_{ij} - \sum_{k=1}^{K} C^k P^k_{ij} \qquad \forall i, j \tag{8}$$

$$s = \sum^{(i,j) \in E} s_{ij} \tag{9}$$

D. Protection 1:1:1 ILP Model

TABLE III
ADDITIONAL VARIABLES

q^k_{ij}	Binary, is set iff edge (i, j) is used by primary backup of flow k
z^k_{ij}	Binary, is set iff edge (i, j) is used by secondary backup of flow k
q^k_g	Binary, is set iff primary backup of flow k is used in graph G_g
z^k_g	Binary, is set iff secondary backup of flow k is used in graph G_g
x^k_g	Binary, is set iff flow k is satisfied in graph G_g

Maximize:

$$\alpha \sum^{g} \sum_{k=1}^{K} x^k_g - s \tag{10}$$

Subject to:

$$\sum_{j=1}^{M} x_{gij}^k - \sum_{j=1}^{M} x_{gji}^k = \begin{cases} x_g^k & \text{if } i = s^k \\ -x_g^k & \text{if } i = d^k \\ 0 & \text{other} \end{cases} \qquad \forall g, i, k \in K_g \tag{11}$$

$$x_{gij}^k + x_{gji}^k \le 1 \qquad \forall g, k, i, j \tag{12}$$

$$x_{gij}^k \ge P_{ij}^k P_g^k \qquad \forall g, i, j, k \tag{13}$$

$$x_{gij}^k = 0 \qquad \forall (i,j) | (i,j) \notin E_g \tag{14}$$

$$q_g^k + z_g^k + P_g^k = x_g^k \qquad \forall g, k \tag{15}$$

$$q_{ij}^k + q_g^k - 1 \le x_{gij}^k \qquad \forall g, k, i, j \tag{16}$$

$$x_{gij}^k + q_g^k - 1 \le q_{ij}^k \qquad \forall g, k, i, j \tag{17}$$

$$z_{ij}^k + z_g^k - 1 \le x_{gij}^k \qquad \forall g, k, i, j \tag{18}$$

$$x_{gij}^k + z_g^k - 1 \le z_{ij}^k \qquad \forall g, k, i, j \tag{19}$$

$$c_{gij} = \sum_{k=1}^{K} C^k (x_{gij}^k + x_{gji}^k) \qquad \forall g, i, j \tag{20}$$

$$c_{ij} \ge c_{gij} \qquad \forall g, i, j \tag{21}$$

$$s_{ij} = c_{ij} - \sum_{k=1}^{K} C^k P_{ij}^k \qquad \forall i, j \tag{22}$$

$$s = \sum^{(i,j)\in E} s_{ij} \tag{23}$$

The objective of the original formulation is modified. With protection schemes in non-triconnected networks there is no way to know in the preprocessing step if a flow can or can not be satisfied in subgraph G_g. It is necessary to include a new set of variables, x_g^k that is set if the flow k is satisfied in subgraph G_g. Eq.10 includes in the first term, the sum of all x_g^k. The coefficient α must be bigger than the biggest value s can take. This is because the model must satisfy the flows whenever it is possible as the higher priority and as second priority minimize the spare capacity used, $\alpha > \sum^{(i,j)\in E} \sum_{k=1}^{K} C^k$.

Eq.11 is modified to take into account the new variable x_g^k, the flow k must be satisfied in subgraph G_g only if $x_g^k = 1$.

Whenever the flow is satisfied in a subgraph G_g, it must use the working path, the primary backup or the secondary backup. This is represented in the model by Eq.15, where q_g^k is for the primary backup and z_g^k is for the secondary backup usage in subgraph G_g.

The primary backup path of flow k is unique. Eq.16 implies that if primary backup of flow k is being used in subgraph G_g then flow variable x_{gij}^k is set only if q_{ij}^k is set. And Eq.31 implies that if the primary backup of flow k is being used in subgraph G_g then q_{ij}^k is set only if x_{fij}^k is set. This two constraints ensures that the primary backup path is constructed for each flow k.

The same thing happens with the secondary backup paths using the z_g^k and z_{ij}^k variables. The 1:1:1 protection scheme allows the full sharing of the protection paths, and there is no constraint on which protection path is used in each subgraph G_g

E. *Protection 1+1+1 ILP Model*

Finally, we consider the case of dedicated protection (1+1+1). The difference between this formulation and the previous one is that the spare capacity cannot be shared with only one exception. We consider the case of non-triconnected networks, then partially disjoint paths must be used for the backup paths. This implies that if both backup paths share one link the spare capacity can be shared on that link. This makes the 1+1+1 protection scheme the most restrictive scheme in terms of capacity sharing. This will be reflected in the results, this scheme is the most expensive one. Eq. 35 shows that if at least one of the two backup paths of flow k uses link (i, j), then r_{ij}^k is set. Eq. 36 computes the total spare capacity per link as the sum of the r_{ij}^k variables multiplied by the capacity demand C^k.

TABLE IV
ADDITIONAL VARIABLES

r_{ij}^k	Binary, is set iff link (i, j) is used by primary and/or secondary backup of flow k

Maximize:

$$\alpha \sum^{g} \sum_{k=1}^{K} x_g^k - s \tag{24}$$

Subject to:

$$\sum_{j=1}^{M} x_{gij}^k - \sum_{j=1}^{M} x_{gji}^k = \begin{cases} x_g^k & \text{if } i = s^k \\ -x_g^k & \text{if } i = d^k \\ 0 & \text{other} \end{cases} \qquad \forall g, i, k \in K_g \tag{25}$$

$$x_{gij}^k + x_{gji}^k \le 1 \qquad \forall g, k, i, j \tag{26}$$

$$x_{gij}^k \ge P_{ij}^k P_g^k \qquad \forall g, i, j, k \tag{27}$$

$$x_{gij}^k = 0 \qquad \forall (i,j) | (i,j) \notin E_g \tag{28}$$

$$q_g^k + z_g^k + P_g^k = x_g^k \qquad \forall g, k \tag{29}$$

$$q_{ij}^k + q_g^k - 1 \leq x_{gij}^k \qquad \forall g, k, i, j \tag{30}$$

$$x_{gij}^k + q_g^k - 1 \leq q_{ij}^k \qquad \forall g, k, i, j \tag{31}$$

$$z_{ij}^k + z_g^k - 1 \leq x_{gij}^k \qquad \forall g, k, i, j \tag{32}$$

$$x_{gij}^k + z_g^k - 1 \leq z_{ij}^k \qquad \forall g, k, i, j \tag{33}$$

$$c_{ij} = s_{ij} + \sum_{k=1}^{K} C^k P_{ij}^k \qquad \forall g, i, j \tag{34}$$

$$2r_{ij}^k \geq q_{ij}^k + z_{ij}^k \qquad \forall i, j, k \tag{35}$$

$$s_{ij} = \sum_{k=1}^{K} C^k r_{ij}^k \qquad \forall i, j \tag{36}$$

$$s = \sum^{(i,j)\in E} s_{ij} \tag{37}$$

V. Main Results

Different analysis were performed on three mesh-type non-triconnected networks topologies shown in Fig. 7. Each network has a traffic demand consisting in one flow (service) between every two nodes requiring one unit of capacity. This means that the total number of flows K will be given by $K = \binom{N}{2}$.

The working paths are determined using a shortest path algorithm. For each network we show results of the required spare capacity using either a 1+1+1 protection scheme, 1:1:1 protection scheme and both restoration schemes. We compare performance in terms of the recovery index R and in terms of relative spare capacity allocated. The relative spare capacity is the spare capacity normalized by the total working capacity expressed as a percentage.

The four models formulated in the previous section where implemented using preprocessing routines in Python that generate the different instances of the models for each network topology. All the instances where solved using CPLEX with computation times below 45 minutes in a personal computer with Intel i7 processor and 8Gb of RAM.

Table V reports main results, where the first column (w) shows the total allocated working capacity, the second column (s), the total allocated spare capacity, the third column, the amount of survived scenarios, and the last column, the total number of single/dual link failure scenarios.

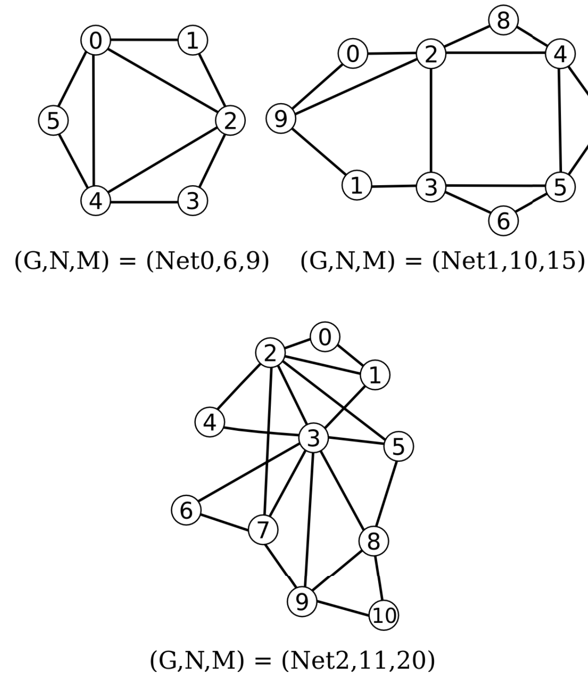

Fig. 6. Networks topologies

TABLE V
RESULTS

Network	Scheme	w	s	Survived Scenarios	Total Scenarios
Net0	1+1+1	21	91	33	45
	1:1:1	21	23	33	45
	1+R (centralized)	21	23	42	45
	1+R (distributed)	21	30	42	45
Net1	1+1+1	66	346	74	120
	1:1:1	66	134	74	120
	1+R (centralized)	66	135	115	120
	1+R (distributed)	66	180	115	120
Net2	1+1+1	99	334	174	210
	1:1:1	99	125	174	210
	1+R (centralized)	99	122	206	210
	1+R (distributed)	99	197	206	210

The 1+1+1 protection scheme always needs more spare capacity than the other schemes. It can be seen how the shared backup paths scheme 1:1:1 can help to decrease the total spare capacity allocated. Nevertheless the number of single/dual link failure scenarios tolerated by the 1:1:1 protection scheme is always the same than the 1+1+1 protection scheme. The restoration schemes have better performance in terms of the recovery index in the three cases. This is because restoration can deal with more failure scenarios than protection schemes in non-triconnected networks. But, the required spare capacity by restoration schemes is always at least the spare capacity needed by the 1:1:1 protection scheme. The centralized restoration show the same performance in terms of recovery index than the distributed version but using

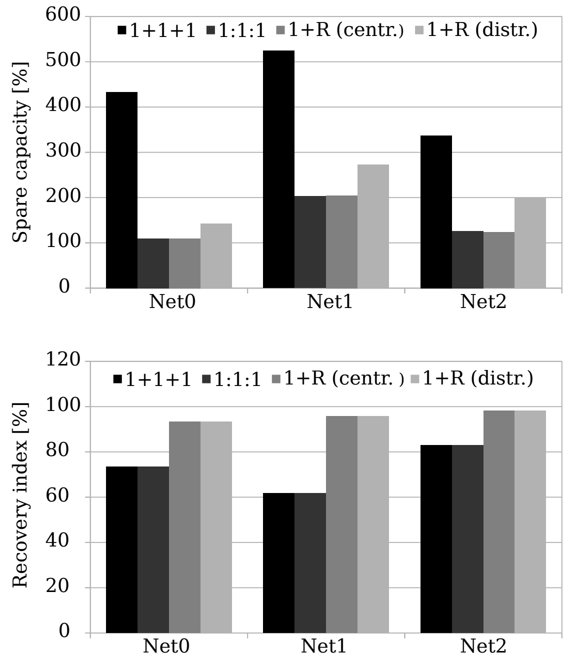

Fig. 7. Results

almost the same spare capacity than the shared protection scheme. This results suggests that a centralized restoration scheme is a good alternative for shared backup paths protection since it can survive more dual-link failure scenarios using almost the same spare capacity.

VI. Conclusion and future work

In this work we described the spare capacity problem in optical networks for different survivability strategies taking into account single and dual link failures scenarios. Dedicated and shared protection schemes were analyzed in addition to centralized and distributed restoration schemes. We formulated the spare capacity problem for these strategies using integer linear programming methods. Finally we used these formulations in order to analyze the performance of protection schemes and restoration schemes in three optical networks topologies. We showed that restoration schemes can increase the number of survived dual link failures scenarios in non-triconnected networks. We also showed that for distributed restoration scheme at least 30% more spare capacity is needed than in the centralized restoration scheme for this three network topologies. This results suggest that centralized schemes can help in optical networks link-failure tolerance allocating less capacity than distributed schemes. Centralized restoration is not yet an option in commercial optical networks. Nevertheless as software optical networks are evolving rapidly, in the near future this kind of features may be available. As software defined optical networks rely on centralized network planning and managing, a centralized restoration reactive scheme could be a cost-effective alternative to shared backup paths protection. In future works we will investigate how software defined optical networks can make use of centralized restoration in order to decrease development and operation costs in non-triconnected networks.

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