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Incremental Spare Capacity Allocation for Optical Networks Restoration

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Abstract— **Survivability of optical networks is one of the most relevant planning problems due to its impact on actual deployment cost. Indeed, survivability can only be achieved by deploying spare resources that will only be used under failure scenarios. 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 takes too much time, which increases the probability of a second fiber cut. In this paper, we consider dual link failure scenarios and analyse the spare capacity allocation problem for restoration schemes, which have the potential to achieve better survivability performance than protection schemes in non-triconnected networks. However, since the traditional global optimization approach is not practical for large networks, we propose an incremental optimization approach that can find sub-optimal solutions in practical times even in large networks.**

Keywords— **Telecommunications, Communications, Combinatorial Optimization, Planning, Networks, Optical Networks, Survivability**

1 Introduction

Survivability is the ability of a network to continue to function during and after a natural or man-made disturbance and 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, which is used to reroute connections interrupted 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 failures [1], in particular on the case of optical link failures (i.e. fiber cuts). In the last years, several works have also considered dual link failures [2, 3, 4] as typical repair times for fiber cuts are large, thus, increasing the probability of a dual fiber cut scenario in large transport networks, 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-failure 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 to all (100%) possible dual link failure scenarios can result in huge costs as it requires triconnected optical networks [4], where each connection can be established through either one of three completely disjoint paths. Triconnected networks tend to allocate spare capacity by increasing the number of network links. These links can require the deployment of new fiber optic cables which is extremely expensive. Commercial optical transport networks are not typically triconnected because of this reason. Instead, network operators prefer increasing the spare capacity on already available fibers as it is much cheaper than deploying new fiber cables. Indeed, network capacity is typically enlarged today by only upgrading terminal equipment on the same fiber cable.

Even if protection schemes are widely used due to their simplicity, they tend to reserve much spare capacity to guarantee survivability on all possible failure scenarios. Besides, the working capacity, which is allocated for the original connection path, cannot be reused 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.

Spare capacity allocation is known to be a very complex problem and its global optimization is not practical in large networks. Authors in [12] use a sub-optimal approach by successively routing demands backup paths. This approach works fine for protection schemes but it is not practical for restoration schemes.

In this paper, we model and analyse the problem of allocating minimum spare capacity for survivability using restoration schemes. We present an Integer Linear Programming (ILP) model for global optimization of this problem and then propose a sub-optimal approach that outperforms the former in computation time.

2 Survivability Strategies

Survivability is the ability of the network to recover services when some kind of disruptive event has occurred. In optical networks, the most often disruptive events are links failures due to fiber cuts. Survivability can be addressed by path protection schemes or path restoration schemes, which re-route the lost connection flow over a different (undisrupted) path. Spare capacity must be allocated in both strategies for protection/restoration paths.

Protection schemes for dual link recovery need two backup paths, in triconnected networks these backup paths and the working path can be mutually disjoint. In biconnected networks, three disjoint paths may not exist, so partially disjoint paths must be used [13]. In protection schemes, spare capacity can be shared between backup paths if they are never used simultaneously, this scheme is called *1:1:1 Protection* [4, 13]. However, working capacity can never be shared in protection schemes.

In restoration schemes, spare capacity must be allocated along the network to guarantee that for each dual-failure scenario there is enough capacity left to establish a restoration path. In triconnected networks, this leads to 100% service recovery, while in non-triconnected networks, 100% recovery is not feasible. Restoration schemes allow full capacity sharing, where two paths, namely working and restoration paths, can share their capacity if never used simultaneously.

Whenever a working path is interrupted, its capacity can be released from the non-interrupted links. 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 every restoration path is independent from any other path. As aresult, in non-triconnected networks, restoration schemes can achieve better performance than protection schemes in terms of the number of double link failure scenarios they can survive.

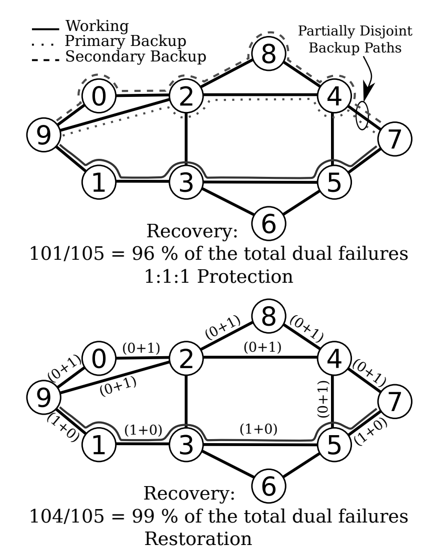

Figure 1: Survivability in biconnected network

In Figure 1 we illustrate the case of a biconnected network with only one flow, where $(w + s)$ represents the working w and the spare s capacity allocated per link in a restoration scheme. For 1:1:1 protection, seven spare capacity units are needed for the primary and secondary backup paths. Since a double link failure that includes the (4,7) link and any other link of the working path can not be recovered only the 96% of the dual-link failure scenarios are covered. If a shared restoration scheme is being used, then eight spare capacity slots are needed but the 99% of the dual failure scenarios are covered.

3 Centralized versus Distributed Restoration

Restoration schemes can achieve better recovery performance than protection ones. Restoration schemes select a route for each disrupted flow after the disruption 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. Blocking can happen and depends on which equipment routes first, this is shown in Figure 2.

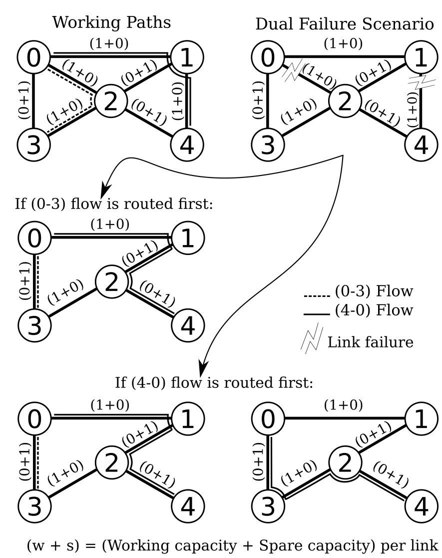

Figure 2: Blocking on distributed restoration scheme

In Figure 2 a five node graph is shown, with two flows, 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 $< 4, 1, 0 >$. We will use the (v_s, v_d) to represent a bidirectional link between vertices v_s and v_d and we will represent paths as a vertex indexes sequences $< v_0, v_1, ...v_i, ..., v_r >$. 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.

4 The Spare Capacity Allocation Problem

The Spare Capacity Allocation (SCA) problem consists in finding the minimal spare capacity needed to guarantee network survivability. As discussed before, 100% survivability to dual link failures can only be achieved in triconnected networks.

An optical network can be represented by an undirected graph $G = (V, E)$ of N nodes, M links and K flows. 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_{ij}^k, where $P_{ij}^k = 1$ if the working path of flow k uses link $(i,j) \in E$, and $P_{ij} = 0$ otherwise. As each dual link failure leads to a new topology, each scenario can be modelled as a new graph based on G where the links that failed are removed from E. This leads to a multi-graph structure $\mathbf{G} = \{G_g\} = \{(V_g, E_g)\}$ where each sub-graph G_g has a node set $V_g = V$, and link set E_g and represent a particular dual link failure scenario. This is illustrated in Figure 3.

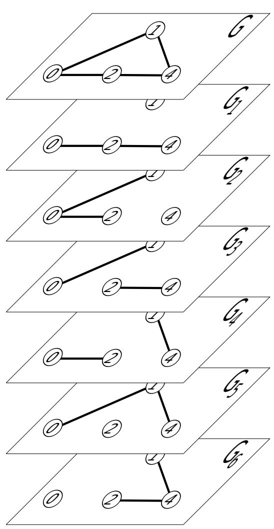

Figure 3: Multi-graph representation

In a given sub-graph G_g, each flow k can or cannot use its working path. This is represented by the P_g^k coefficients, where $P_g^k = 1$ if the flow k can be routed over its working path in sub-graph G_g. Moreover, a flow must use the working path whenever it is available, so these coefficients also indicate that the working path of flow k must be used in sub-graph G_g.

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

The total capacity allocated on link (i,j) for sub-graph G_g is referred as c_{gij}, and it depends on all flows routed through (i,j) for sub-graph 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 sub-graphs. Note that two paths routed on the same sub-graph cannot share capacity, but two paths routed on different sub-graphs 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 surviving the maximum possible number of dual link failure scenarios.

5 Spare Capacity Allocation Schemes

In this section, we first introduce an ILP formulation for the SCA problem assuming a centralized restoration. This model takes into account all possible dual link failure scenarios and finds a solution that minimize the total spare capacity while satisfying each flow whenever possible (if at least one path exists). As this model grows exponentially with the number of links in the network and exponentially with the number of flows, then it is not practical for computing large networks. We have called this method *Global optimization Spare Capacity Allocation* (GOSCA). Next, we propose a sub-optimal approach that approximates the global optimization case by solving the spare capacity allocation problem incrementally for each dual link failure scenario. This approach still makes use of an ILP formulation for each scenario but the partial solution is saved and used as an initial solution for the next scenario (sub-graph). The main advantage of this approach is that it dramatically reduces the computation time as it will be shown in Section 6. We have named this method as *Incremental Optimization Spare Capacity Allocation* (IOSCA).

5.1 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 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 two links subtracted from it. The number of sub-graphs G_g is $\binom{M}{2}$. Once the $\mathbf{G}$ set is computed the P_g^k coefficients can be generated. For each sub-graph G_g the working paths of the K flows must be evaluated, if working path wp^k is available on sub-graph 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 sub-graph G_g. This is, if at least one path from s^k to d^k exists in sub-graph G_g, then $k \in K_g$ and if no path can be found then $k \notin K_g$.

Table 1: Data

$N, M, K, \|\mathbf{G}\|$	Number of nodes,links, flows, graphs
$\mathbf{G} = \{G_g\}$	Double failure graphs set
C^k	Capacity demands
s^k, d^k	Source/destination nodes of flow k
P_{ij}^k	Working paths link coefficients
P_g^k	Working paths availability coefficients
$\mathbf{K_g}$	Path availability for flow k in graph g

5.2 Global Optimization Model

5.2.1 ILP Model

Table 2: Variables

x_{gij}^k	Binary, is set iff edge (i,j) is used by flow k in sub-graph G_g.
c_{gij}	Integer, allocated capacity in edge (i,j) in sub-graph 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:

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

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

$$x_{gij}^k \geq P_{ij}^k P_g^k \qquad \forall g, i, j, k \tag{4}$$

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

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

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

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

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

The objective is given by Eq. 10 of the model, which aims at minimizing the total spare capacity s along all the network. This value takes into account all the spare capacity allocated on each link to guarantee the best achievable recovery performance. 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.

5.2.2 Flow constraints:

The flow variables x_{gij}^k represent the route of flow k in sub-graph G_g, where $x_{gij}^k = 1$ implies that the flow k goes through link (i,j) in sub-graph 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 sub-graph 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, which means that a link can never be used twice for one flow.

The working paths must be used whenever available. Constraint Eq. 4 forces flow variables to $x_{gij}^k = 1$ if the working path of flow k is available in G_g and link (i,j) is part of that path. $P_g^k = 1$ is one only when working path of flow k is available on sub-graph G_g and P_{ij}^k 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 sub-graph 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.

5.2.3 Capacity constraints:

The total capacity needed on link (i,j) in sub-graph 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 sub-graphs, then the total capacity allocation per link is the largest allocation along all the sub-graphs, Eq. 7. This total capacity per link c_{ij} includes working capacity and spare capacity, constraint Eq. 8 represents this relation. The total spare capacity is the sum of all the spare capacities allocated per link, Eq.9.

5.3 Incremental Optimization Model

This approach finds a suboptimal solution by splitting the problem into simpler ones, the model used here solves the SCA problem for one sub-graph each time. The whole problem can be solved by solving successively each sub-graph, each solution has its impact on the final solution. To model this, we introduce the S_{ij} variables, these variables are modified after each iteration to reflect the expend of spare capacity of each particular solution. These variables are used as an initial solution for the next scenario. In this way, when the last scenario on the list is solved the whole problem is solved. However, note that this approach strongly depends on the order that the sub-graphs are solved.

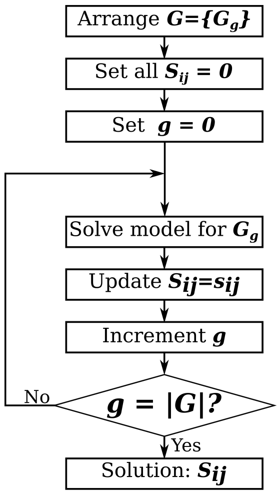

Figure 4: Incrtemental optimization algorithm flow chart

5.3.1 ILP model

Table 3: Variables

x_{ij}^k	Binary, is set iff edge (i,j) is used by flow k
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:

$$s \tag{10}$$

Subject to:

$$\sum_{j=1}^{M} x_{ij}^k - \sum_{j=1}^{M} x_{ji}^k = \begin{cases} 1 & \text{if } i = s^k \\ -1 & \text{if } i = d^k \\ 0 & \text{other} \end{cases} \quad \forall i,k \in K_g \tag{11}$$

$$x_{ij}^k + x_{ji}^k \leq 1 \qquad \forall k,i,j \tag{12}$$

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

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

$$c_{ij} = \sum_{k=1}^{K} C^k (x_{ij}^k + x_{ji}^k) \qquad \forall i,j \tag{15}$$

$$c_{ij} \leq s_{ij} + \sum^{k \in \mathbf{K_g}} C^k P_{ij}^k \qquad \forall i,j \tag{16}$$

$$s_{ij} \geq S_{ij} \qquad \forall i,j \tag{17}$$

$$s = \sum^{(i,j) \in E} s_{ij} \tag{18}$$

5.3.2 Flow constraints:

This ILP model solves the SCA problem for one graph, then the g index can be removed from the constraints. Eq. 11, 12, 13 and 14 are the simplified versions of the flow constraints of the Global Optimization Model.

5.3.3 Capacity constraints:

Constraint Eq. 15 computes the total capacity allocated per link. The spare capacity per link can be calculated as the subtraction of the working capacity from the total capacity allocated. Since there is pre-installed spare capacity S_{ij} this relationship is modified, the spare capacity per link must be grater or equal than the total installed capacity minus the working capacity of that link. Eq. 16 reflects this relationship. Moreover, the spare capacity per link must be grater or equal than the pre-installed spare capacity, Eq. 17. Finally, the total spare capacity is the sum of all the spare capacities allocated per link, Eq.18.

6 Main Results

Analysis were performed on five mesh-type non-triconnected networks topologies shown in Figure 5. Each network has a traffic demand consisting in one flow between every two nodes requiring one unit of capacity. The working paths are determined using the shortest path algorithm.

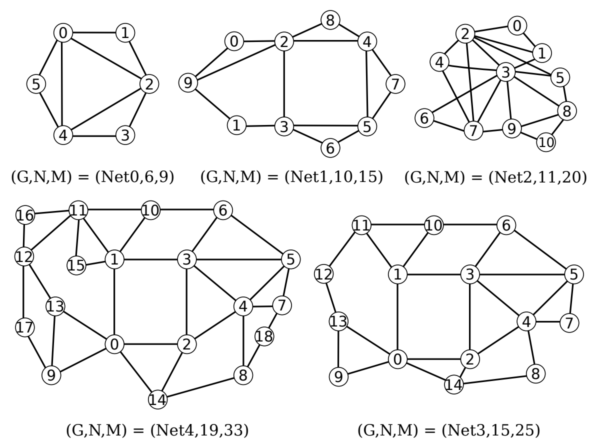

Figure 5: Network topologies used for results

The IOSCA method needs to order the graphs set **G**, we use two ordering criteria *Worst Scenario First (WCF)* and *Best Scenario First (BSF)*. Each scenario disrupts a number of flows if we use this as metric, the scenarios can be ordered in a descendent manner (*WCF*) or in an ascendant manner (*BSF*). Additionally, random orders where generated as random permutations of the original set.

For each network we show results of the required spare capacity for centralized restoration scheme using the *Global Optimization model*, the *WSF-IOSCA*, the *BSF-IOSCA* method and a solution obtained using the best of 50 random ordered graphs sets. We compare this solutions with a shortest path spare capacity allocation *(SP-SCA)* that uses the shortest path algorithm to reserve spare capacity for the shortest path of interrupted demands in each sub-graphs. This method can survive the same number of dual link failure scenarios.

The models where implemented using routines in Python that generate the different instances of the models for each network topology. All the instances where solved using CPLEX with in a personal computer with Intel i5 processor and 4GB of RAM.

Table 4: Results

	Net0		Net1		Net2		Net3		Net4	
Scheme	**s**	**Comp. time [s]**	**s**	**Comp. time [s]**	**s**	**Comp. time [s]**	**s**	**Comp. time [s]**	**s**	**Comp. time [s]**
GOSCA	23	0,18	135	4,11	130	21,93	334	500,30	545	2144,12
WSF-IOSCA	26	0,01	150	2,20	134	6,13	370	20,19	652	86,8
BSF-IOSCA	27	0,01	139	2,00	147	6,34	353	20,04	611	87,1
50xRandom-IOSCA	25	-	138	-	132	-	353	-	597	-
SPSCA	27	0,20	163	0,80	161	1,01	423	1,27	787	7,3

Table 4 reports main results, where the first column (s) shows the total spare capacity, the second column (Computation time), the total computation time needed to get the solution.

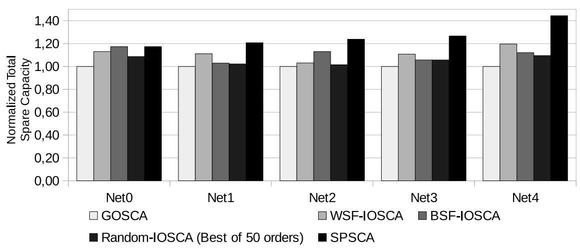

Figure 6: Normalized spare capacity allocated

In Figure 6 we show the total spare capacity allocated by each method for the five networks topologies. The total spare capacity is normalized to the capacity allocated by the *GOSCA*. The global optimization always allocates less capacity than the others methods due to its global optimization nature. The *SPSCA* has the worst performance in terms of total capacity allocated because this method doesn't take into account the pre-installed spare capacity in each routing. Between this two methods is the *IOSCA* that can get better results than the *SPSCA*.

7 Conclusions and Future Work

A global optimization approach for the SCA problem has shown impractical for its application on large networks, instead an incremental optimization approach can be used to reduce the computation time. In Table 4 we shown how this sub-optimal approach can outperform the global optimization in terms of computation time. Besides, Figure 6 showed how *IOSCA* can achieve good solutions compared with a *SPSCA* algorithm. Nevertheless, it can be seen that the solution in the *IOSCA* approach strongly depends on the ordering. Moreover, *WSF* and *BSF* are not good ordering criteria since better solutions can be found by random ordering. In this paper, we have shown that an incremental optimization approach can be used to achieve practical optimization of the SCA problem for the case of restoration schemes. In future works we will try to find a good ordering criterion plus a heuristic to avoid local optimum.

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