Protection, Routing, Spectrum and Core Allocation in EONs-SDM for Efficient Spectrum Utilization

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***Abstract*—The use of protection in elastic optical networks (EONs) with spatial division multiplexing (SDM) can lead to under-utilization of the spectrum, since a high number of resources is reserved for protection. In this paper, we propose an algorithm that employs minimum interference routing, FIPP p-cycle, optical traffic grooming, and spectrum overlap to increase the efficiency in spectrum utilization in protected EONs-SDM. Extensive simulation results show that the proposed algorithm prevents the formation of network bottlenecks and reduces the resources used for protection.**

***Index Terms*—Protection, Elastic Optical Network, Space Division Multiplexing, Traffic Grooming, FIPP P-cycle.**

I. Introduction

Elastic optical network (EONs) with Spatial division multiplexing (SDM), EON-SDM, is a promising solution to deal with the increasing demands of bandwidth. The ability to flexibly allocate the spectrum will allow this type of network to handle traffic demands with varying bandwidth requirements. In addition, the adoption of SDM will provide greater capacity. The larger the network capacity and carried traffic, the greater is the need for effective protection schemes to avoid massive loss of data. However, the employment of spare capacity for the protection of working paths reduces available resources for working paths, leading to the blocking of incoming requests.

Optical traffic grooming (TG) reduces the spectrum waste caused by the use of guard bands, improving the spectral efficiency. In EONs, traffic grooming is a technique that combines multiple connections in an optical path without the need of guard bands between them [1]. Optical traffic grooming benefits from the flexibility provided by switches which add multiple optical paths on a single transmitter and switch them together. Traffic grooming is performed transparently without conversion from the optical to the electrical domain.

The utilization of spare capacity can be further reduced by using spectrum overlap (SO) for protection paths. If two connections have disjoint working paths, and their backup paths traverse two adjacent optical paths on a fiber, the two optical paths may overlap in spectrum. The overlapping frequency slot is shared between adjacent optical paths in the time domain; it is occupied by at most one of the adjacent optical paths at a time. The use of spectrum overlapping does not require traffic grooming since the elastic transponder can adjust the position of the guard band used, increasing the width of the spectrum used by one backup path while decreasing the spectrum used by another adjacent backup path.

P-cycle is a protection technique with pre-configured backup resources. P-cycle can protect all the on-cycle spans as well as straddling spans. P-cycle combines the advantage of mesh networks with the restoration speed of ring networks [2]. Failure-Independent Path Protecting (FIPP) p-cycles is a particular case of p-cycle for protecting path. They furnish protection to end-to-end working path with end nodes on the p-cycle. Although a p-cycle uses a large amounts of resources, a single FIPP p-cycle can protect a large number of working paths reducing the use of spare capacity. While the use of FIPP p-cycle involves pre-connected paths, another protection scheme called shared backup path protection (SBPP) involves only pre-planned paths. In the event of failure, an SBPP scheme needs to dynamically establish the backup path while for a FIPP scheme the backup path is already established. Moreover, the restoration time of SBPP is much longer than that of p-cycle scheme.

The employment of FIPP p-cycles can lead to rapid saturation of links resources. A promising approach is to employ minimum interference routing in the creation of FIPP p-cycle to promote a balanced utilization of resources. Minimum interference algorithms generate connections along paths that least interfere with incoming requests for connection establishment. The use of straddling FIPP p-cycles, whenever possible, improves the use of resources availability for protection.

Protecting optical networks requires a considerable amount of reserved and unused resources. In this paper, we propose a routing, spectrum, and core assignment (RSCA) algorithm called the FIPP p-cycle, Routing, Spectrum and Core Assignment (FRSCA) algorithm that employs minimum interference routing to create FIPP p-cycle for reducing the rejection of future requests. Besides, the proposed algorithm uses traffic grooming and spectrum overlap in the definition of p-cycles. The combined use of p-cycle FIPP, traffic grooming, and spectrum overlap reduces spectrum waste in protected EON SDM, which, in turn, reduces the blocking of requests. The employment of minimum interference routing in the creation of FIPP p-cycles improves the use of available resources to realize protection. The FRSCA algorithm differs from the algorithm in [3] by the use of minimum interference and differs from the algorithm in [4] by the use of traffic grooming and spectrum overlap.

The rest of the paper is structured as follow. Section II reviews related work. Section III introduces the proposed algorithm. Section IV evaluates the performance of the proposed algorithm and Section V concludes the paper.

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II. Related Work

There are several related papers on traffic grooming [5]–[8], however, only in [3] traffic grooming was employed for the protection of EON-SDM.

Liu *et al.* [5] proposed an approach that uses a first-fit policy to assign spectrum for the working paths, and the last-fit policy to assign spectrum for the backup paths. This approach allows spectrum overlap between backup paths. It is called elastic separate-protection-at-connection (ESPAC) and it provides traditional backup sharing, and it also offers opportunity for spectrum sharing enabled by the elasticity of the transponders.

In [6], it was presented a three-layered auxiliary graph model to address mixed-electrical-optical grooming under dynamic traffic scenario. By adjusting the edge weights of the auxiliary graph, they achieved various traffic-grooming policies for different purposes. Also, they proposed two spectrum reservation schemes to utilize the capacity of a transponder efficiently.

Costa *et al.* [7] addressed the routing, modulation level, and spectrum allocation problem by the use of electric and optical traffic grooming associated with the control of spectral modulation in dynamic traffic scenario. They proposed an algorithm that seeks the largest groom possible amount of traffic using higher levels of modulation.

Ye *et al.* [8] proposed a distance-adaptive and fragmentation-aware optical traffic grooming algorithm for elastic optical networks. The algorithm had as objective the maximization of the spectral efficiency while considering transmission reach constraints.

The authors in [3] investigated the problem of protection in space division multiplexing elastic optical networks using FIPP p-cycle, traffic grooming and spectrum overlap. However, minimum interference FIPP p-cycle was not studied.

Table I presents a comparison between the related work and the proposed algorithm (FRSCA).

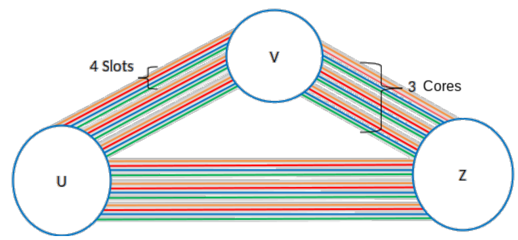
Table I: Comparison of related works

Approach	Protection	SDM	TG	SO
Liu *et al.* [5]	Yes	No	Yes	Yes
Zhang *et al.* [6]	No	No	Yes	No
Costa *et al.* [7]	No	No	Yes	No
Khodashenas *et al.* [9]	No	No	Yes	No
Ye *et al.* [8]	No	No	Yes	No
Oliveira *et al.* [3]	Yes	Yes	Yes	Yes
FRSCA algorithm	Yes	Yes	Yes	Yes

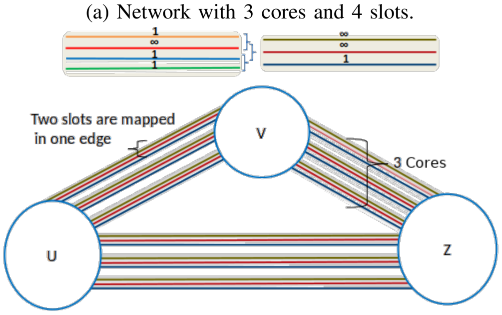
III. The Algorithm

This section introduces the FIPP p-cycle, Routing, Spectrum and Core Assignment (FRSCA) algorithm, which employs FIPP p-cycles, minimum interference, traffic grooming and spectrum overlap for path protection. A lightpath is established if and only if it can be protected by an FIPP p-cycle, which can have both on-cycle and straddling links. A single FIPP p-cycle can protect several disjoint working paths. FRSCA algorithm differs from the STOP algorithm [3] by the creation of straddling FIPP p-cycles, whenever possible, which prevents p-cycles and working paths to use the same links, minimizing the blocking of future requests.

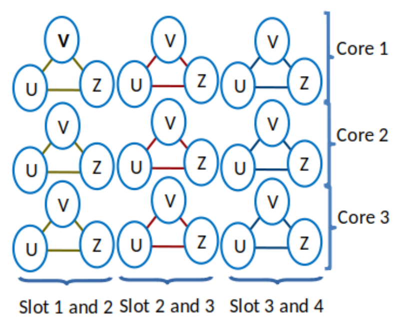
The FRSCA algorithm decides on the establishment of lightpaths in an FIPP p-cycle protected network. Traffic grooming, spectrum overlap, and, minimal interference routing are assumed in the creation of working as well as backup paths. The FRSCA algorithm considers the allocation of the same spectrum into each fiber along the route of a lightpath (continuity constraint), as well as the necessity of slots being contiguously allocated in the spectrum (contiguity constraint).



(a) Network with 3 cores and 4 slots.



(b) Set of edges are mapped in to one edge, following to contiguity constraint. In this example, two edges are mapped into one edge.



(c) Graphs generated.

Figure 1: Transforming multigraph in graphs

The FRSCA algorithm models the spectrum availability in the network as a labeled multigraph (Fig. 1a). A edge represents a slot which is considered available if not allocated by any existing lightpath and the crosstalk on that slot is lower than a pre-defined threshold value. In Fig. 1b, the multigraph is transformed into other multigraph with $N - b + 1$ edges (Fig. 1c), with b being the bandwidth demand in slots. These multigraphs is then transformed into $N - b + 1$ graphs. In Fig. 1c, the original multigraph is transformed into $C \times (N - b + 1)$ graphs. Each edge in these graphs represents a combination of b slots. This representation assures spectrum contiguity in the solution. In these graphs, an ∞ label means that at least one out of b slots is either allocated or has unacceptable crosstalk on it, whereas value smaller than ∞ means that all slots are available for allocation.

The notation used in this paper is summarized in Table II.

Table II: Notation

s: source node;

d: destination node;

b: bandwidth demand in slots;

N: number of slot between two nodes;

C: number of cores;

V: set of nodes;

$e_{u,v,n}$: the n^{th} edges connecting u and v;

$E = \{e_{u,v,n}\}$: set of edges;

F: number of physical links;

$G = (V, E, W)$: labeled multigraph composed by a set of nodes V, a set of edges E and a set of edge weight W, $|E| = C \cdot N \cdot F$. The edges connecting two vertices of G represent the N slots in the link connecting two network nodes;

$r(s, d, b)$: request from the node s to the node d with bandwidth demand b;

$w(e_{u,v,n})$: weight of the edge $e_{u,v,n}$; $w(e_{u,v,n}) > 1$ if the n^{th} slot in the link connecting OXC u and v is free and $w(e_{u,v,n}) = \infty$ if the slot is already allocated;

$W = \{w(e_{u,v,n})\}$:set of edge weights;

$\widetilde{V} = V$: set of nodes;

$\widetilde{e}_{u,v} \in \widetilde{E}$: edge connecting $\widetilde{u}$ and $\widetilde{v}$;

$\widetilde{e}_{\widetilde{u},\widetilde{v}} = \{e_{u,v,n}\} \in E$ is a chain such that $e_{u,v,n}$ is the least ordered edge, $e_{u,v,n+b}$ is the greatest ordered edge and $|\widetilde{e}_{u,v}| = b$;

$\widetilde{w}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}})$: weight of the edge $\widetilde{e}_{\widetilde{u},\widetilde{v}}$;

$\widetilde{W} = \widetilde{w}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}})$;

$\widetilde{G}_{n,b} = (\widetilde{V}, \widetilde{E}, \widetilde{W})$: the n^{th} labeled graph such that $\widetilde{E}$ is the set of edges connecting $\{\widetilde{u}, \widetilde{v}\} \in \widetilde{V}$ and $\widetilde{W}$ is the set of costs associated to $\widetilde{E}$. The edges in $\widetilde{E}$ correspond to the mapping of b edges in G starting at the $n^{th} edge$;

$\sigma = |\{\widetilde{G}_{n,b}\}| = C \times (N - b + 1)$: number of graphs extracted from the multigraph;

$\tau(G, C, b) = \{\widetilde{G}_{n,b}\}$: function which produces all σ graphs from G;

P_n: chain of $\widetilde{G}_{n,b}$ such that the source node s is the least ordered node and d is the greatest ordered node;

$W(P_n)$: $\sum_{\widetilde{e}_{\widetilde{u},\widetilde{v}} \in \{P_n\}} \widetilde{e}_{\widetilde{u},\widetilde{v}}$: the weight of the path P_n (the sum of the weights of all the edges in the chain);

$W_{P_{s,d}}$ = weight of the shortest path between s and d;

$\varpi(P_n, T_{u,v}, r(s, d, b))$: p-cycle in $T_{u,v}$ which $P_{T_{u,v}}$ are link disjoint to P_n and satisfies the request of bandwidth b;

$\delta(G, C, b, P_n) = \{\widetilde{G}_{n,b}\}$: function which produces all graphs from G, considering that slots of protection can be shared, since the working paths (P_n) of the connections are physically disjoint (spectrum overlap);

T_n: chain of $\widetilde{G}_{n,b}$ such that the source node s is the least ordered node and d is the greatest ordered node;

$T_{u,v}$: set of all p-cycles between vertices u and v in G;

$P_{T_{u,v}}$: set of all paths protected by p-cycle $T_{u,v}$;

H_{P_n}: set of all slots used by path P_n;

$H_{P_{T_{u,v}}}$: set of all slots used by all paths protected by p-cycle $T_{u,v}$;

$T = \{T_{u,v}\}$: set of all established p-cycles;

$\varphi(\widetilde{G}_{n,b_m}, P_n, r(s, d, b))$: shortest straddling FIPP p-cycle between s and d in $\widetilde{G}_{n,b}$, considering that $H_{P_{T_{u,v}}}$ is disjointness to P_n ;

$\gamma(\widetilde{G}_{n,b_m}, P_n, r(s, d, b))$: shortest FIPP p-cycle between s and d in $\widetilde{G}_{n,b}$, considering that $H_{P_{T_{u,v}}}$ is disjointness to P_n ;

$W(T_n)$: $\sum_{\widetilde{e}_{\widetilde{u},\widetilde{v}} \in \{T_n\}} \widetilde{e}_{\widetilde{u},\widetilde{v}}$: the weight of the backup paths T_n (the sum of the weights of all the edges in the chain);

$W_{T_{s,d}}$ = weight of the backup path which protects the path between s and d;

The FRSCA algorithm is introduced in Algorithm 1. Line 1 transforms the multigraph into $C \times (N - b + 1)$ graphs. Line 2 computes the shortest path for all graph $\widetilde{G}_{n,b}$ and chooses the one with the lowest cost. Line 3 selects the path among all shortest paths that has the lowest weight value. If the weight of all shortest path is ∞ (Line 5), it was not possible to find a path under the contiguity constraint for the demand b, then the connection cannot be routed due to insufficient subcarriers, and the request is blocked (Line 6). Otherwise, an FIPP p-cycle to protect the lightpath to be established is sought (Line 8). In case there is an FIPP p-cycle, the lightpath is established (Line 9) and the corresponding edges in the multigraph G have their weight changed to ∞ (Line 10) meaning that the slots were allocated to protect one more path. If the active p-cycles cannot protect the new path, then a new p-cycle needs to be created. Line 11 transforms the multigraph into $C \times (N - b + 1)$ graphs, considering spectrum overlap and traffic grooming for protecting slots. A straddling shortest FIPP p-cycle to protect the lightpath to be established should be created (Line 12). In the case a straddling shortest FIPP p-cycle cannot be created, a shortest FIPP p-cycle to protect the lightpath to be established should be established (Line 14). When no p-cycle can be established to protect the lightpath, the request is blocked (Line 16). Otherwise, the working path as well as the FIPP p-cycle (Line 20) are established to satisfy the request and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 21).

The complexity of the FRSCA algorithm is analyzed as follows. The complexity of transforming the original multi-graph in graphs is $O(E + V)$. For a primary path, the Dijkstra algorithm is executed in $C \times N - b$ graphs, the complexity of the Dijkstra algorithm is $O(E + V logV)$. For p-cycle, the Yen's algorithm is executed in $C \times N - b$ graphs. The complexity of Yen's algorithm is $O(K \times V \times (E + V logV))$. In the worst case, the complexity of the FRSCA algorithm is:

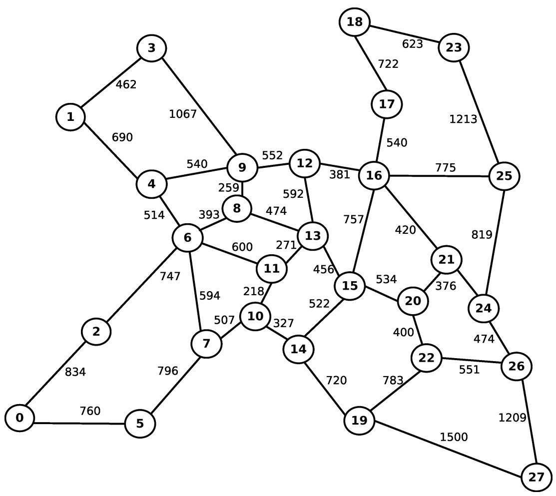
Algorithm 1 FRSCA

Input: $G, r(s, d, b)$
Output: Working path and FIPP p-cycle
1: $\Delta(G, C, b)$
2: $(W(P_n), P_n) =$ ShortestPath$(\widetilde{G'}_{n,b}, r(s, d, b)) \quad \forall n \in \sigma$
3: $W_{P_{s,d}} = W(P_n) | \; \forall i \; W(P_n) \leq W(P_i)$
4: $w(e_{u,v,i}) = \infty \quad \forall \{u, v\} \in P_i$
5: **if** $W_{P_{s,d}} = \infty$ **then**
6: Blocks request $(r(s, d, b))$
7: **else**
8: **if** $\exists \varpi(P_n, T, r(s, d, b))$ **then**
9: Establishes request $(r(s, d, b))$ **as** P_n **and** T_n
10: **else**
11: $\delta(G, C, b)$
12: $(W(T_n), T_n) = \varphi(\widetilde{G''}_{n,b}, P_n, r(s, d, b))$
13: **if** $W_{T_{s,d}} = \infty$ **then**
14: $(W(T_n), T_n) = \gamma(\widetilde{G''}_{n,b}, P_n, r(s, d, b))$
15: **if** $W_{T_{s,d}} = \infty$ **then**
16: Blocks request $(r(s, d, b))$
17: **end if**
18: **end if**
19: **if** $W_{T_{s,d}} \neq \infty$ **then**
20: Establishes request $(r(s, d, b))$ **as** P_n **and** T_n
21: $w(e_{u,v,i}) = \infty \quad \forall \{u, v\} \in T_i$
22: **end if**
23: **end if**
24: **end if**

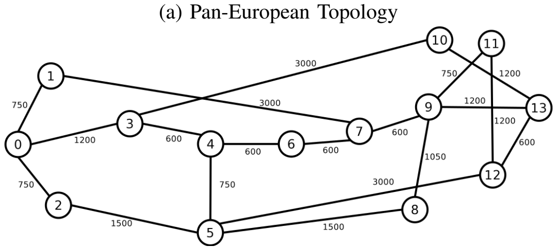
$O(K \times V \times (\|E\| + \|V\| log \|V\|)$.

IV. Performance Evaluation

In order to evaluate the performance of the proposed algorithm in multi-core networks, simulations were derived. The FlexGridSim [10] simulator was employed in this simulation. For each scenario, at least ten simulations were run and in each simulation 100,000 requests were generated. The network load was varied from 25 to 500 erlangs. Seven types of requests were employed 25 Gbps, 50 Gbps, 125 Gbps, 200 Gbps, 500 Gbps, 750 Gbps and 1 Tbps. The links were composed by MCFs with 7 core and each core was divided into 320 slots. Confidence intervals were derived using the independent replication method, and a 95% confidence level was adopted. The mean arrival rate and the mean holding time were adjusted to simulate specific loads in erlangs. The modulation format BPSK was used with 1 bit per symbol. It is employed for extensions of up to 4000 km.



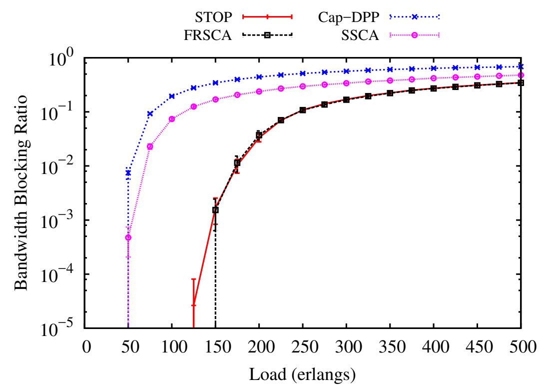
(a) Pan-European Topology



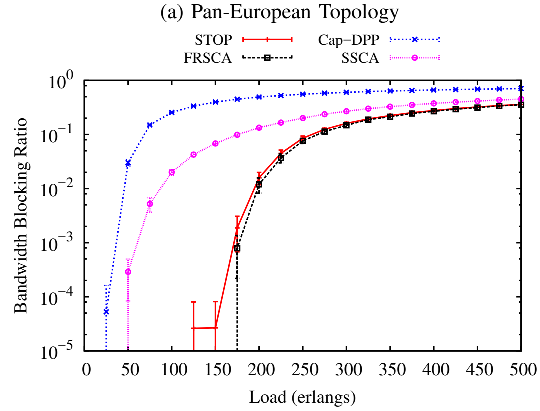
(b) NSF Topology

Figure 2: Topologies

The topology used in the simulations were the Pan-European (Figure 2a) and the NSF (Figure 2b) topologies. The NSF topology has 14 nodes and 20 links whereas the Pan-European topology has 28 nodes and 39 links (Fig. 2). The numbers on the links represent the length of the link in kilometers. Results are compared to those derived by the Cap-DPP [11], SSCA [12] and STOP [3] algorithms. The Cap-DPP uses a crosstalk-aware provisioning strategy with dedicated path protection, SSCAM algorithms [12] provides protection using shared backup paths. The STOP algorithm uses a shortest FIPP p-cycle employing traffic grooming and spectrum overlap to provide protection. None of these algorithms adopts minimum interference routing in the creation of FIPP p-cycles. While CaP-DPP employs dedicated path protection and SSCA employs shared backup path, the STOP and FRSCA algorithms employ FIPP p-cycles for protection. Although p-cycles use a greater amount of resources than shortest paths, the use of traffic grooming and spectrum overlap allows p-cycles to use a small amount of resources. The employment of minimal interference by the FRSCA algorithm allows load balancing in the network. The metrics considered for evaluation of the algorithms are the bandwidth blocking ratio (BBR), the crosstalk per slot (CpS) and the number of hops of backup path.



(a) Pan-European Topology



(b) NSF Topology

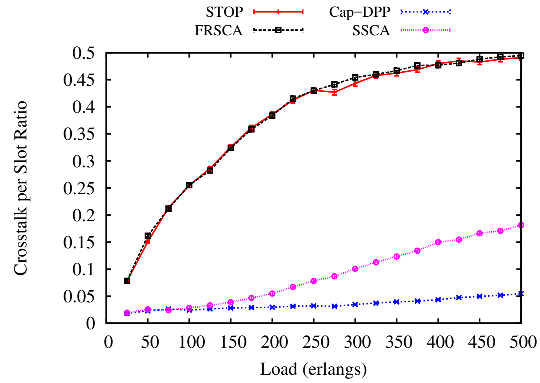
Figure 3: Bandwidth blocking ratio

Fig. 3 shows the bandwidth blocking ratio (BBR) for the Pan-European and NSF topologies. BBR is defined as the percentage of bandwidth (traffic) blocked over the total bandwidth requested during the entire simulation period:

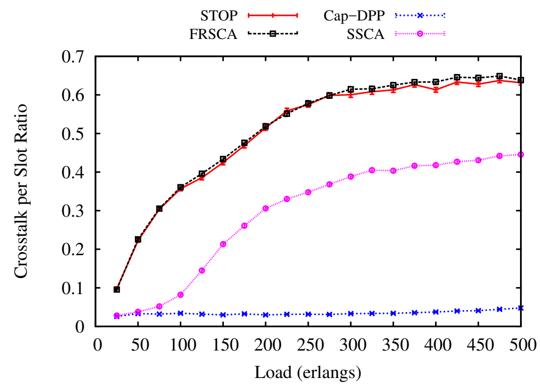
$$BBR = \frac{\sum BandwidthBlocked}{\sum TotalBandwidth} \quad (1)$$

For the Pan-European topology (Fig. 3a), the SSCA and Cap-DPP algorithms saturate the network under loads of 100 erlangs. Due to the high connectivity of the Pan-European topology there is no blocking until 50 erlangs. While Cap-DPP and SSCA start blocking requests for loads of 50 erlangs, STOP and FRSCA start blocking only for loads of 125 and 150 erlangs, respectively. The FRSCA and STOP algorithms produce less blocking than do the SSCA and Cap-DPP algorithms. This is due to the adoption of traffic grooming and spectrum overlap, which reduces the utilization of spare capacity. In the STOP algorithm, the sharing of p-cycle leads to low blocking, being very close to the blocking generated by the FRSCA algorithm under high loads. Until load of 150 erlangs, the FRSCA algorithm does not produce blocking, as a consequence of the adoption of spectrum overlap, traffic grooming and minimum interference. While traffic grooming and spectrum overlap reduce the use of spare capacity, the minimum interference routing improves the allocation of resources for protection. FRSCA combines the advantages of minimum interference, traffic grooming and spectrum overlap, producing less blocking.

For the NSF topology (Fig. 3b), the Cap-DPP and SSCA algorithms saturate the network under loads of 75 and 125 erlangs, respectively. While Cap-DPP and SSCA start blocking requests under loads of 25 and 50 erlangs, respectively, the STOP and FRSCA algorithms start blocking only under loads of 125 and 175 erlangs, respectively. The STOP and FRSCA produce less 42% blocking than the Cap-DPP and SSCA algorithms. This is due to the use of traffic grooming and spectrum overlap, that reduce the problem of spectrum utilization efficiency. Meanwhile, FRSCA produces about 2% less blocking than STOP between loads of 50 and 175 erlangs and between loads of 175 and 275 erlangs. The combination of minimum interference routing, spectrum overlap and traffic grooming in the FRSCA algorithm evinces the advantages, when compared with the others algorithms presented in the paper.



(a) Pan-European Topology



(b) NSF Topology

Figure 4: Crosstalk per slot ratio

Fig. 4 shows the crosstalk per slot ratio (CpS) for the Pan-European and NSF topologies. The CpS is defined as the average ratio between the pairs of frequency slots used that have the same frequency and are located in adjacent cores (Arrangement of Crosstalk, AoC) and the total of slots used [13]:

$$CpS = \frac{AoC}{\#UsedSlots} \tag{2}$$

For the Pan-European topology (Fig. 4a), the STOP and FRSCA algorithms produce the highest CpS values, because these algorithms accept more connections than do the other algorithms. These connections generate greater crosstalk interference. The CpS generated by the STOP and FRSCA algorithms increase quickly with the load increase since the higher the number of hops used, the higher are the resource utilization and the CpS. Until loads of 100 erlangs, the SSCA and Cap-DPP algorithms produce similar values of CpS, despite they generated different BBR. Although the FRSCA and STOP algorithms generated high CpS, connections are established only if the working and backup paths have acceptable inter-core crosstalk.

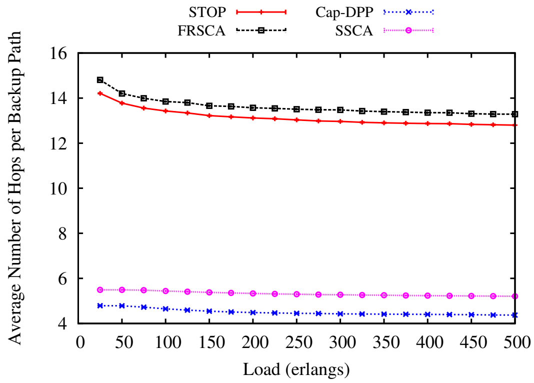
For the NSF topology (Fig. 4b), as for the Pan-European topology, the FRSCA algorithm produce the highest CpS values. This CpS is a consequence of the high network utilization, generated by the high number of requests accepted. The SSCA algorithm produce CpS values closer to those generated by FRSCA and STOP, and they block more requests. The smaller the BBR values, the greater is the utilization and, consequently, the greater is the crosstalk ratio. The use of FIPP p-cycles produces stronger crosstalk per slot, because the creation of p-cycles uses more resources and the slots used have more adjacent slots. Although the backup paths are not active, the CpS must be evaluated since crosstalk will be generated and must be at an acceptable level when the backup path are used.

Fig. 5 shows the average number of hops in the allocated lightpath of backup paths for the Pan-European and NSF topologies. The average number of hops in the allocated lightpath of backup paths ratio is defined by Eq. 3.

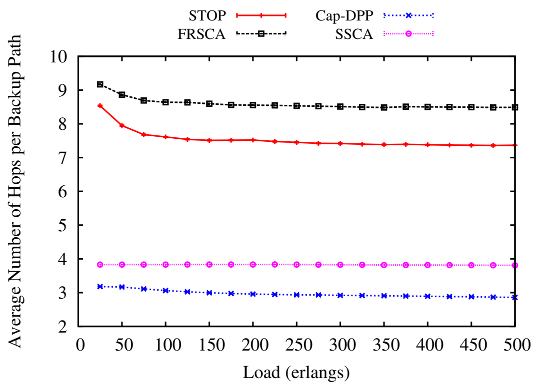
$$ANHBP = \frac{\sum \#BackupHops}{\sum \#AcceptedRequests} \tag{3}$$

For the Pan-European topology (Fig. 5a), the FRSCA and STOP algorithms required a higher number of hops for the backup path. However, the sharing of p-cycles paths makes better use of network resources, since a p-cycle protects a higher number of working paths. SSCA and Cap-DPP algorithms use the lowest average number of hops because they do not use FIPP p-cycles, whereas the FIPP p-cycle algorithms needs two paths for its creation. This feature, however, is what makes the FIPP p-cycle algorithm capable of providing protection for a higher number of working paths.

For the NSF topology (Fig. 5b), the FRSCA and STOP algorithms also produce the highest number of hops for the



(a) Pan-European Topology



(b) NSF Topology

Figure 5: Hops of backup path

backup path. The algorithms simulated demand an almost constant number of hops allocated per backup path regardless of the network load. The number of backup paths allocated by the FRSCA algorithm is always higher than that allocated by the STOP algorithms. It happens due to the cost of the creation of straddling FIPP p-cycles. The number of backup paths allocated by the SSCA algorithms is always higher than those allocated by Cap-DPP.

V. Conclusion

In this paper, we presented the FRSCA algorithm for the protection of elastic optical networks with spatial multiplexing, which employs traffic grooming, spectrum overlap, the minimum interference routing and FIPP p-cycle. Results showed a reduction in the BBR produced by the algorithm proposed when compared to other algorithms. The BBR values produced by the proposed algorithm shows the benefit of using minimum interference routing in the creation of FIPP p-cycle. The values of the CpS produced by the proposed algorithm remained high due to the high utilization of network resources.

Acknowledgments

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References

[1] G. Zhang, M. De Leenheer, and B. Mukherjee, "Optical traffic grooming in ofdm-based elastic optical networks [invited]," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 4, no. 11, pp. B17–B25, Nov 2012.

[2] R. Asthana, Y. Singh, and W. Grover, "p-cycles: An overview," *Communications Surveys Tutorials, IEEE*, vol. 12, no. 1, pp. 97–111, First 2010.

[3] H. M. N. S. Oliveira and N. L. S. d. Fonseca, "Spectrum overlap and traffic grooming in p-cycle algorithm protected sdm optical networks," in *2018 IEEE International Conference on Communications (ICC)*, May 2018, pp. 1–6.

[4] H. M. N. S. Oliveira and N. L. S. da Fonseca, "The minimum interference p-cycle algorithm for protection of space division multiplexing elastic optical networks," in *2016 8th IEEE Latin-American Conference on Communications (LATINCOM)*, Nov 2016, pp. 1–6.

[5] M. Liu, M. Tornatore, and B. Mukherjee, "Survivable traffic grooming in elastic optical networks shared protection," *IEEE, Journal of Lightwave Technology*, vol. 31, no. 6, pp. 903–909, 2013.

[6] J. Zhang, Y. Ji, M. Song, Y. Zhao, X. Yu, J. Zhang, and B. Mukherjee, "Dynamic traffic grooming in sliceable bandwidth-variable transponder-enabled elastic optical networks," *Journal of Lightwave Technology*, vol. 33, no. 1, pp. 183–191, Jan 2015.

[7] L. R. Costa and A. C. Drummond, "Novo algoritmo RMLSA com roteamento multihop em redes Ópticas elásticas," in *Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos (SBRC) 2016*, Salvador, Bahia, may 2016.

[8] Z. Ye, A. N. Patel, P. N. Ji, and C. Qiao, "Distance-adaptive and fragmentation-aware optical traffic grooming in flexible grid optical networks," in *2014 OptoElectronics and Communication Conference and Australian Conference on Optical Fibre Technology*, July 2014, pp. 355–356.

[9] P. Sayyad Khodashenas, J. Comellas, S. Spadaro, and J. Perelló, "Dynamic source aggregation of subwavelength connections in elastic optical networks," *Photonic Network Communications*, vol. 26, no. 2, pp. 131–139, Dec 2013. [Online]. Available: https://doi.org/10.1007/s11107-013-0415-1

[10] P. M. Moura and A. C. Drummond, "FlexGridSim: Flexible Grid Optical Network Simulator," http://www.lrc.ic.unicamp.br/FlexGridSim/.

[11] Y. Tan, R. Zhu, H. Yang, Y. Zhao, J. Zhang, Z. Liu, Q. Qu, and Z. Zhou, "Crosstalk-aware provisioning strategy with dedicated path protection for elastic multi-core fiber networks," in *2016 15th International Conference on Optical Communications and Networks (ICOCN)*, Sept 2016, pp. 1–3.

[12] A. Muhammad, G. Zervas, D. Simeonidou, and R. Forchheimer, "Routing, spectrum and core allocation in flexgrid sdm networks with multi-core fibers," in *Proc. of ONDM Conf.*, Stockholm, Sweden, May 2014, pp. 192–197.

[13] S. Fujii, Y. Hirota, H. Tode, and K. Murakami, "On-demand spectrum and core allocation for reducing crosstalk in multicore fibers in elastic optical networks," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 6, no. 12, pp. 1059–1071, Dec 2014.