Spectrum Overlap and Traffic Grooming in P-cycle Algorithm Protected SDM Optical Networks

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***Abstract*—The Space division multiplexing (SDM) in elastic optical networks brings new challenges for protection of networks since a lightpath can span multiple cores. Although previous studies have studied protection in SDM elastic optical networks (EON), no work has considered the joint use of p-cycle, traffic grooming and spectrum overlap for these networks. In this paper, we investigate the problem of protection in space division multiplexing elastic optical networks, generating primary paths and p-cycles. The proposed solution allows a more efficient use of network, keeping crosstalk acceptable. Results derived via simulation show that the proposed spectrum overlap, traffic grooming and FIPP p-cycle algorithm can keep the quality of transmission and yet decrease the blocking of connections.**

***Index Terms*—Protection, Multi-core Fiber, Elastic Optical Network with Space Division Multiplexing, FIPP p-cycle, Traffic grooming.**

I. Introduction

In elastic Optical Networks (EONs), different bandwidth demands can be accommodated due to the employment of a fine-grained multiplexing of the spectrum based on orthogonal frequency division multiplexing (OFDM). Moreover, elastic optical networks with space division multiplexing (SDM) provides much greater capacity when compared to conventional single mode fiber systems. SDM involves using spatial channels and can be realized by using multi-core fiber (MCF).

The routing and spectrum assignment (RSA) problem is a fundamental problem in elastic optical networks (EON). In RSA, the contiguous and continuous allocation of the spectrum on all links of the selected route must be observed [1]. Moreover, in SDM EON, it is possible to allocate one or more cores for the establishment of a connection. The inclusion of the space degree of freedom adds another dimension to the RSA problem becoming the routing, spectrum and core allocation (RSCA) problem. In RCSA, additional issues such as inter-core crosstalk should be taken into account. Inter-core crosstalk happens when the same spectrum is used in adjacent cores in MCF. If on one hand, Space-Division Multiplexing (SDM) technology allows the increase of network capacity, on the other hand, MCF produces physical impairments that reduces the spectrum usability.

The Internet backbone is composed by optical fibers spanning long distances and high transmission rates. In optical transport networks that carry huge amounts of traffic, redundancy is a common approach to enhance the end-to-end (E2E) service availability. p-Cycle is an attractive protection schemes, and has been intensively investigated in the past years. p-Cycles combine the properties of ring-like recovery speed and the efficiency of restorable mesh networks. p-Cycles protect the working capacity on the span they cover, as shared protection rings, and, unlikely rings, they protect the working capacity of off-cycle spans which have their end-points on the p-cycle (straddling spans). A type of p-cycle of special interest is the failure-independent path protecting p-cycle (FIPP p-cycles) which provides fully pre-connected protection paths in optical networks. FIPP p-cycles offer all the advantages of shared backup path protection (SBPP) and in addition the protection path is pre-configured.

Traffic grooming (TG) is a technique widely adopted to increment the performance of traditional wavelength division multiplexed (WDM) networks. Traffic grooming in EONs increases spectral efficiency, the utilization of network devices and reduces network cost and power consumption. However, traffic grooming can lead to the need of more optical-to-electrical-to-optical (O-E-O) conversions as well as traffic processing at the intermediate core routers [2]. In EON, traffic grooming combines various connections in an optical path without the need of having guard bands between them [3]. Moreover, traffic grooming increases the utilization of bandwidth variable transponders (BVTs) and multi-flow transponders (MFTs) in advanced EONs [4].

Spectrum overlap allows two backup lightpaths to use the same cores, links and spectrum, since the working paths of the two connections are physically disjoint [5]. The combination of traffic grooming and spectrum overlap leads to significant gain in spectrum utilization, decreasing the blocking of connections.

In this paper, we propose an algorithm called Spectrum overlap, Traffic grOoming and FIPP P-cycle (STOP) for providing protection in SDM-EONs. The algorithm creates protection paths, using the FIPP p-cycle technique, spectrum overlap and traffic grooming. Results show that the proposed algorithm promotes protection effectively without increasing blocking significantly. The key advantages of p-cycles are pre-configured protection, switching speed and operational simplicity similar to ring networks. Therefore, FIPP p-cycle protection has great potentiality to play a key role in SDM-EON protection.

This rest of the paper is organized 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

Klonidis *et.al.* [6] introduced the RCSA problem (called RSMLSA by the authors) and listed the challenges due to the use of the space dimension. A network control framework was also presented to endorse the usage of centralized solutions based on software defined networks and path computation elements (PCE). In [7], research on space division multiplexing fibers and network components was reviewed. They introduced two figures of merit aiming at a quantitative evaluation of technologies such as amplifiers, fan-in/fan-out multiplexers, transmitters, switches, and SDM nodes. In [8], it was introduced an RCSA algorithm based on the connected component labelling (CCL) algorithm. Spectrum fitting policies are also proposed to be jointly employed with the CCL algorithm.

The authors in [9] introduced an algorithm based on p-cycle to provide failure-independent path protection in elastic optical networks with space division multiplexing. However, spectrum overlap is not considered. In [10] [11], it was proposed an algorithm to provide Failure-independent path protecting p-cycle with minimum interference for path protection in elastic optical networks using space division multiplexing.

Hirota *et.al.* [12] divides the RSCA problem into the routing, and core and spectrum assignment (SCA) problems, and introduces a K-shortest path based pre-computation method as the routing solution. They proposed SCA methods with crosstalk awareness. In [13], it was proposed an algorithm to provide protection using p-cycle FIPP and modulation. The authors evaluated the energy efficiency of the algorithm combining p-cycle and adaptive modulation. Sasaki *et.al.* [14] numerically analyzed the crosstalk behaviors over various effective index differences between non-identical cores. The authors in [15] evaluated the advantages of using the extra dimension introduced by space-division multiplexing (SDM) for dynamic bandwidth-allocation in a flexible optical network. In [16], a RSCA problem for flexgrid optical networks is proposed for the network planning problem using integer linear programming (ILP) formulation as well a heuristic. Spectrum overlap jointly with p-cycle FIPP was studied in [17].

None of these studies used the p-cycle protection technique combined with spectrum overlap and traffic grooming in space division elastic optical networks as shown in this paper.

III. The STOP Algorithm

The algorithm introduced in this subsection, called Spectrum overlap, Traffic grOoming and FIPP P-cycle (STOP), decides on the establishment of lightpaths in protected networks. In this paper, we assumed that a lightpath is established if and only if it can be protected by a FIPP p-cycle. STOP algorithm extends the FIPPMC algorithm [9], by adding traffic grooming and spectrum overlap and providing low bandwidth blocking ratio and crosstalk per slot ratio.

The following notation will be used to describe the algorithm:

s: source node;

d: destination node;

b: bandwidth demand considering traffic grooming;

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;

$\delta(G, r(s, d, b))$: shortest path between s and d in G that satisfies the request of b slots ;

$w(e_{u,v,n})$: 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;

$\kappa(G, C, b, P_n) = \{\widetilde{G}_{n,b}\}$: 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;

$\Omega(\widetilde{G}_{n,b_m}, P_n, r(s, d, b))$: shortest 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 proposed algorithm models the spectrum availability in the network as labeled multigraph (Fig. 1a) [9]. A label on an edge represents the availability of a slot. In Fig. 1b, the multigraph is divides into C multigraphs, where C is the number of cores. Each of these multigraphs is transformed into multigraphs with $N - b + 1$ edges, (Fig. 1c) where b is the bandwidth demand in slot. Then, each of these multigraphs is transformed into $N - b + 1$ graphs. In other words, the original multigraph (Figure 1c) is transformed into $C \times (N - b + 1)$ graphs (Fig. 1d). Each edges in these graphs represent a combination of b slots. This representation assures spectrum contiguity to the solution. In these graphs, an ∞ label value means that at least one slots is already allocated whereas the value 1 means that all slots are available for allocation.

Algorithm 1 STOP

1: $\tau(G, C, b)$
2: $(W(P_n), P_n) = \delta(\widetilde{G}_{n,b}, r(s,d,b)) \quad \forall n \in \sigma$
3: $\quad W_{P_{s,d}} = W(P_n) | \; \forall i \; W(P_n) \leq W(P_i)$
4: **if** $W_{P_{s,d}} = \infty$ **then**
5: $\quad$ block $r(s,d,b)$
6: **else**
7: $\quad$ **if** $\exists \varpi(P_n, T_{s,d}, r(s,d,b))$ **then**
8: $\quad\quad$ establish $r(s,d,b)$ as P_n and $T_{s,d}$
9: $\quad\quad$ $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in P_i$
10: $\quad$ **else**
11: $\quad\quad$ $\kappa(G, C, b, P_n)$
12: $\quad\quad$ $(W(T_n), T_n) = \Omega(\widetilde{G}_{n,b}, P_n, r(s,d,b))$
13: $\quad\quad\quad$ $W_{T_{s,d}} = W(T_n) | \; \forall i \; W(T_n) \leq W(T_i)$
14: $\quad\quad$ **if** $W_{T_{s,d}} = \infty$ **then**
15: $\quad\quad\quad$ block $r(s,d,b)$
16: $\quad\quad$ **else**
17: $\quad\quad\quad$ establish $r(s,d,b)$ as P_n and T_n
18: $\quad\quad\quad$ $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in P_i$
19: $\quad\quad\quad$ $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in T_i$
20: $\quad\quad$ **end if**
21: $\quad$ **end if**
22: **end if**

The STOP algorithm is introduced in Algorithm 1. Line 1 transforms the multigraph into $C \times (N - b + 1)$ to graphs. Line 2 computes the shortest path for all graph $\widetilde{G}_{n,b}$ and choses the least costs one. Line 3 selects the path among all shortest paths that has the lowest weight value. If the weight of all shortest path is ∞, 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 (Line 4), and the request is blocked (Line 5). Otherwise, a FIPP p-cycle to protect the lightpath to be established is sought (Line 7). In case there exists a FIPP p-cycle, the lightpath is established (Line 8) and the corresponding edges in the multigraph G have their weight changed to ∞ (Line 9) 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 the spectrum overlap for protecting slots. A shortest FIPP p-cycle to protect the lightpath to be established should be created (Line 12). In case a shortest FIPP p-cycle can be created, the primary path as well as the FIPP p-cycle (Line 13) are established to satisfy the request and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 14) meaning that the slots were allocated to the newly established lightpath. Alternatively, if no p-cycle can be created to protect the lightpath then the request is blocked (Line 17).

The complexity of the STOP algorithm is analyzed as follows. The complexity of transforming the original multigraph in graphs is $O(E+V)$. For primary path, a Dijkstra algorithm is executed in $C \times N - b$ graphs, Dijkstra complexity 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 [18] is $O(K \times V \times (E + V logV))$. In the worst case, the complexity of the STOP algorithm is $C \times (N - b) \times (E + V logV) + C \times (N - b) \times K \times V \times (E + V logV) + E + V$, since C and N values can be expressed as constant, then the complexity is: $O(K \times V \times (\|E\| + \|V\| log \|V\|)$.

IV. Performance Evaluation

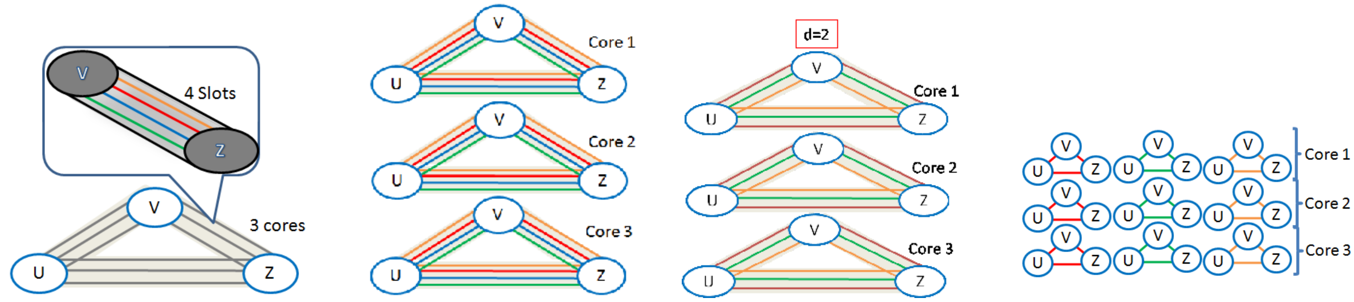
To assess the performance of the STOP algorithm, simulation experiments were employed using the FlexGridSim [19] simulator. In each simulation, 100,000 requests were generated as input and simulations for all the algorithms used the same set of seeds. Seven types of requests were employed 25 Gbps, 50 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 in 320 slots. Confidence intervals were derived using the independent replication method with 95% confidence level. Calls arrive follow a Poisson distribution and are uniformly-distributed among all node-pairs of network. The topology used in the simulations were the USA (Figure 2a) and the NSF (Figure 2b) topologies. The NSF topology has 14 nodes and 20 links whereas the USA topology has 24 nodes and 43 links (Fig. 2). The numbers on the links represent the length of the link in kilometers.

The inter-core crosstalk is a type of interference in which one core causes to another core of the same link, i.e., the ratio of the optical power inserted from adjacent cores to the one divided by the power of the signal already in that core and measured in dB [7]. To calculate the crosstalk (XT) from one core in relation to *n* neighboring cores, in a homogeneous MCF fiber, we used (2). Considering the coupled-power theory [7] [20], and using (1) leads to (2), which was used to ensure the quality of transmission of the connections.

$$h = \frac{2 \cdot k^2 \cdot R}{\beta \cdot D} \tag{1}$$

Equation 1 expresses the mean crosstalk increase per unit length; *h* is the mean crosstalk increase per unit length, *k*, β, *R*, *D* are coupling coefficient, propagation constant, bend radius and core-pitch, respectively.

$$XT = \frac{n\{1 - exp(-(n+1) \cdot 2 \cdot h \cdot L\}}{1 + n\{exp(-(n+1) \cdot 2 \cdot h \cdot L)\}} \tag{2}$$



(a) Network with 3 cores and 4 slots. (b) The Multigraph, separated by cores, each one representing 4 slots. (c) The Multigraph in that set edges are mapped in to one edge, contiguity constraint. (d) Graphs generated.

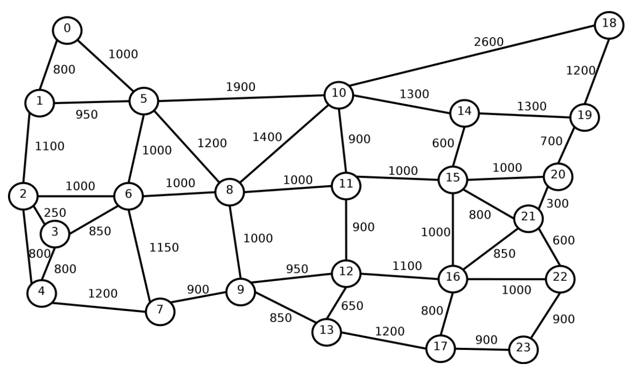
Fig. 1: Transforming multigraph in graphs

Equation 2 uses the mean crosstalk increase per unit length (1), the length of the fiber (L) and n represents the number of neighboring cores.

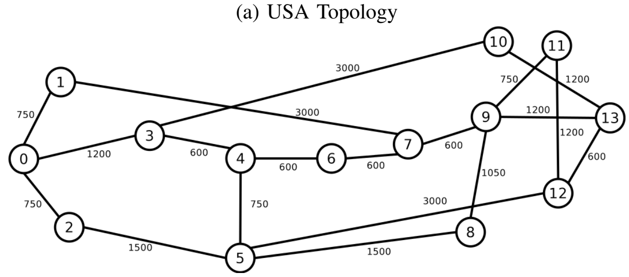
We assumed a maximum value for n equals to 6, $k = 2 \times 10^{-5}$, R = 50 mm, $\beta = 4 \times 10^6$ e D = 45 μm. As in [7], we considered a threshold of around -24 dB as an acceptable XT. The worst case of crosstalk occurs at central core (or any other core that has the largest number of neighboring cores), since it receives undesired interference from all others adjacent cores. In our simulation, we assume that the spectrum of each core is fully utilized.

In the figures, the curves labeled "SSCA" show results for networks using the algorithm based on the methods proposed in [12] which uses a K-shortest paths algorithm to compute routes. In this paper, we use K = 3. The curves labeled "FIPPMC" show the results for networks using the FIPPMC algorithm [9] which FIPPMC decides on the establishment of lightpaths in an FIPP p-cycle. The curves labeled "MIFMC" show the results for networks using the algorithm MIFMC [10], [11]. The MIFMC algorithm prioritizes the use of straddling p-cycles in order to generate minimum interference to reduce rejections of future requests. The curves labeled "STOP" show the results for networks using the proposed algorithm.

Fig. 3 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. While BPP and SSCA start blocking requests under loads of 50 erlangs, FIPPMC starts blocking only under loads of 125 erlangs, and STOP starts blocking requests under loads of 200 erlangs. Under such loads the difference between the BBR produced by the STOP algorithm and those produced by the FIPPMC, SSCA and BPP algorithm are two, three and four order of magnitude, respectively. The low BBR produced by STOP evinces the benefits of considering traffic grooming and spectrum overlap. The high BBR produced by BPP is a consequence of not sharing backup paths. Besides that the BPP and SSCA produced high BBR values because they do not use the multigraph representation of the spectrum that allows decisions to be made



(a) USA Topology



(b) NSF Topology

Fig. 2: Topologies

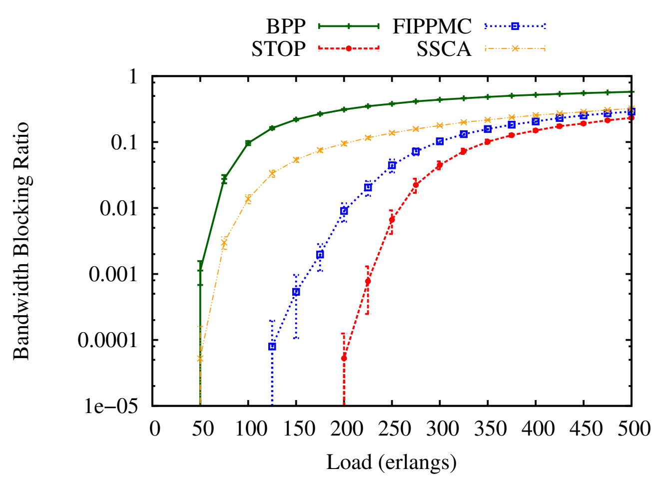


Fig. 3: Bandwidth blocking ratio for the USA topology

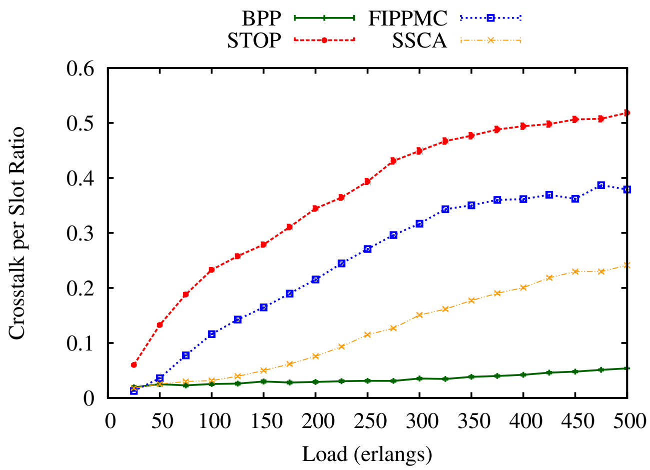


Fig. 4: Crosstalk per slot ratio for the USA topology

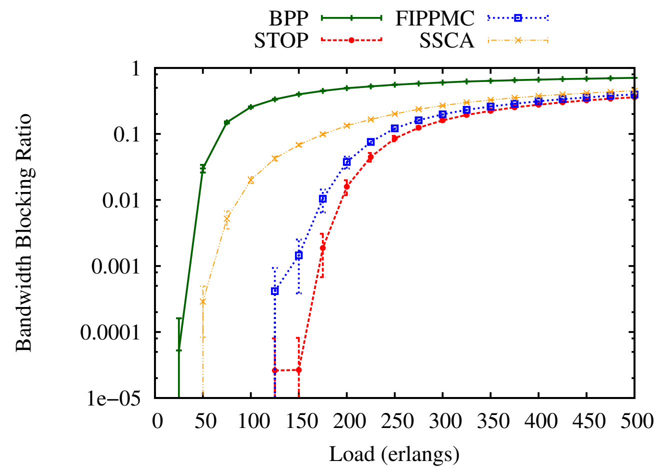


Fig. 5: Bandwidth blocking ratio for the NSF topology

by considering a fine spectrum allocation granularity, thus avoiding fragmentation of the spectrum. Although FIPPMC and STOP use FIPP p-cycle and the multigraph representation of the spectrum, the low BBR produced by STOP occurs because only STOP employs traffic grooming and spectrum overlap.

The use of seven cores generates intercore crosstalk. Fig. 4 shows the "Crosstalk per Slot" (CpS) as a function of the load for the USA topology. The crosstalk value for each spectrum slot is defined as the ratio of actual crosstalk index to the maximum value of crosstalk index. The crosstalk ratio is defined as the average value considering all spectrum slots [1]. The CpS is not considered when the slot is reserved but not used. The generated CpS by the STOP algorithm starts at a 0.04 and increases until 0.51 while that generated by the FIPPMC algorithm starts at 0.01 and increases until 0.37. The generated CpS for the SSCA algorithm starts at 0.01 and increases until 0.39. The generated CpS for the SSCA algorithm starts at 0.01 and increases until 0.24. The STOP algorithm produces the highest CpS values, as a consequence of the high utilization produced. The BPP algorithm produces the lowest CpS values, as a consequence of the high blocking and low utilization produced.

Fig. 5 shows the bandwidth blocking ratio (BBR) as a function of the load for the NSF topology. The low node degree in this topology leads to the creation of bottlenecks and a much faster increase in blocking when compared to the blocking for the USA topology. While BPP and SSCA start blocking requests under load of 25 and 50 erlangs, respectively, FIPPMC and STOP start blocking only under loads of 125 erlangs. Such trend is a consequence of the FIPPMC and STOP algorithms employing FIPP p-cycle and the multigraph representation of the spectrum. Under loads of 125 erlangs, the difference between the BBR values produced by the STOP algorithm and those given by the FIPPMC and SSCA algorithm is almost two order and almost four order of magnitude, respectively. Under high loads of 300 erlangs, the BBR values produced by the STOP is similar to the values produced by the FIPMC and SSCA algorithms.

Fig. 6 shows the Crosstalk per Slot (CpS) as a function of the load for the NSF topology. The CpS generated when employing the NSF topology is higher than that produced when employing the USA topology. However, the curves are similar to those found for the USA topology. The CpS generated by the STOP algorithm starts at a 0.1 value and increases until 0.62. The CpS generated by the FIPPMC algorithm starts at 0.02 and increases until 0.55. The CpS generated by the SSCA algorithm starts at a 0.02 value and increases until 0.43. The BPP algorithm produces the lowest CpS values when compared to the CpS values generated by the other three algorithms, as consequence of producing high blocking and low utilization.

V. Conclusion

Protection is a fundamental problem in optical networks, especially in SDM elastic optical networks. This paper introduced an algorithm to address the problem of dynamic protection in space division multiplexing elastic optical networks

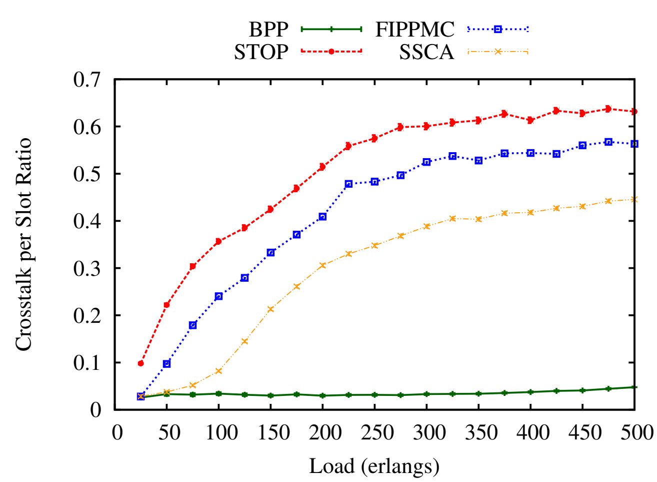


Fig. 6: Crosstalk per slot ratio for the NSF topology

mesh networks and proposed a new algorithm called STOP to recover from one link failures. Simulation results evinces the better performance of the STOP algorithm when compared to the other evaluated algorithms.

Acknowledgments

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