Sharing Spectrum and Straddling p-Cycle FIPP for Protection Against Two Simultaneous Failures in SDM Elastic Optical Networks

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***Abstract*—The introduction of Space division multiplexing (SDM) in optical networks brings new challenges for protection of networks since a lightpath can span multiple cores. In this paper, we investigate the problem of dynamic protection against two simultaneous failures in spacial division multiplexing elastic optical networks. For that, we propose a new path-protection sharing spectrum and straddling p-cycle FIPP algorithm called Sharing Slot and Straddling p-Cycle FIPP (SSSPF). In SSSPF, each connection is assigned one primary path and one link-disjoint backup path. SSSPF is the first algorithm in literature, to provide protection against two simultaneous failure in SDM elastic optical network.**

Keywords*—Protection, Multi-core Fiber, Elastic Optical Network with Space Division Multiplexing, p-cycle FIPP.

I. Introduction

Over the last few years, the capacity limitation of single core optical fibers has motivated the definition of new techniques to increase the traffic capacity in optical fibers leading to the emergence of spacial division multiplexing (SDM). Spacial division multiplexing employs multiple single mode cores placed in a single fiber structure. Space division multiplexing can be realized using multimode fiber (MMF), multicore Fiber (MCF) or few-mode multicore fiber. In MMF, the number of modes supported by a fiber depends on the core size and the refraction index of the fiber cladding. In MCF, each core acts as a single mode fiber.

The routing and spectrum assignment (RSA) problem is a fundamental problem in elastic optical networks (EON). In RSA, there are constraints assuring contiguous and continuous allocation of the spectrum on all links of the selected route [1]. However, in SDM, 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. Moreover, in RCSA additional issues such as inter-core crosstalk should be taken into account. Inter-core crosstalk happens when the same spectrum propagates through adjacent cores in MCF. Elastic optical networks with SDM promises to provide much larger capacity when compared to conventional single mode fiber systems. 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 the most adequate approach to augment 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 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 provide fully pre-connected protection paths in optical networks. FIPP p-cycles offer all the advantages of SBPP and in addition the protection path is pre-configured.

In elastic optical networks, traffic grooming is a technique that combines multiple connections in an optical path without needing guard bands between them [2]. Sharing spectrum is a technique in which two backup lightpaths can use the same cores, links and spectrum, since the working paths of the two connections are physically disjoint [3]. The combination of traffic grooming and spectrum sharing allows significant gain in spectrum utilization, which decreases the blocking of connections.

In this paper, we propose an algorithm called Sharing Slot and Straddling p-Cycle FIPP (SSSPF) for providing FIPP p-cycle protection in SDM-EONs. The algorithm creates protection paths against two simultaneous failures, using the straddling FIPP p-cycle technique, sharing spectrum and traffic grooming. Results show that the proposed algorithm promotes protection effectively without compromising networking blocking. 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.

The 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.

II. Related Work

The emergence of spacial division multiplexing elastic optical networks has motivated several investigations, mainly on RCSA algorithms but only recently protection schemes have been proposed and no other algorithm has been proposed for protection against two failures.

Saridis *et.al.* [4] reviewed research progress on spacial division multiplexing fibers and network components. They introduced two figures of merit aiming for quantitative evaluation of technologies such as amplifiers, fan-in/fan-out multiplexers, transmitters, switches, and SDM nodes. In [6], it is introduced a Routing, Core and Spectrum Assignment (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 [7] introduced an algorithm based on p-cycle to provide failure-independent path protection in elastic optical networks with spacial division multiplexing. However shared slot is not considered. In [8] [9], it is 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.* [10] 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 [11], it is 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.* [12] numerically analyzed the crosstalk behaviors over various effective index differences between non-identical cores. The authors in [13] evaluated the advantages of using the extra dimension introduced by space-division multiplexing (SDM) for dynamic bandwidth-allocation purposes in a flexible optical network. In [14], a routing, spectrum and core allocation (RSCA) problem for flexgrid optical networks is proposed for network planning problem using integer linear programming (ILP) formulation as well a heuristic. The spectrum overlap and p-cycle FIPP was studied in [15] for protection in elastic optical networks.

III. The SSSPF Algorithm

The algorithm introduced in this subsection, called Sharing Slot and Straddling p-Cycle FIPP (SSSPF), decides on the establishment of lightpaths in protected networks. A lightpath is established if and only if it can be protected by a shared path against two failures.

The proposed algorithm models the spectrum availability in the network as labeled multigraph (Fig. 1a). A label on an edge represents the availability of a slot. In Fig. 1b, the multigraph is divided 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, (Fig. 1d) an ∞ label value means that at least one slots is already allocated whereas the value 1 means that all slots are available for allocation.

The following notation will be used to describe the algorithm:

s: source node;

d: destination node;

b: bandwidth demand;

N: number of slots 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;

$G = (V, E, W)$: labeled multigraph composed by a set of nodes V, a set of edges E and a set of edge weight W, $|E| = C \cdot N \cdot |V|$. 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 $n^{th} edge$;

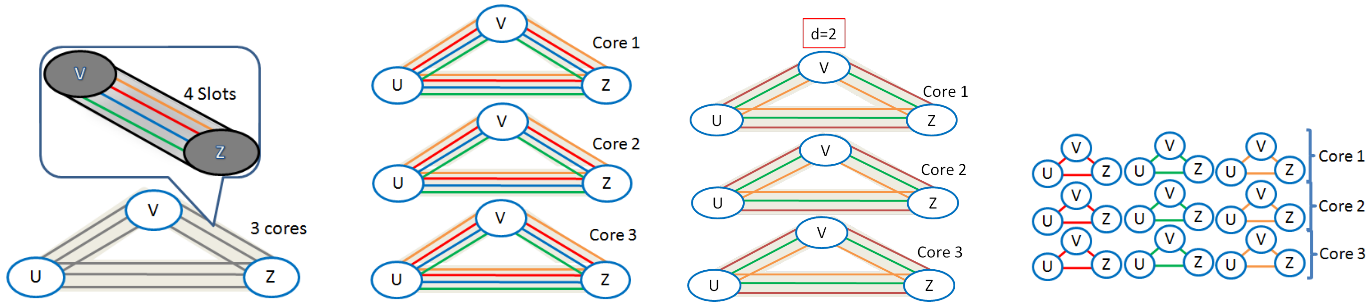
$\sigma = |\{\widetilde{G}_{n,b}\}| = C \times (N-b+1)$: number of graphs extracted from the multigraph;

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



(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

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

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 backup path between vertices u and v in G;

$P_{T_{u,v}}$: set of all paths protected by backup path $T_{u,v}$;

$T = \{T_{u,v}\}$: set of all established backup paths;

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

$\rho(\widetilde{G}_{n,b}, P_n, T_{u,v}, r(s, d, b))$: shortest straddling p-cycle in $T_{u,v}$ which $P_{T_{u,v}}$ are link disjoint to P_n and satisfies the request of bandwith b;

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

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

The algorithm SSSPF 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 least costs one. If the weight of the shortest path is ∞, it was not possible to find a path under the contiguity constraint for the demand b. Line 3 selects the path among all shortest paths that has the lowest weight value. In case the weight of all shortest path is ∞ (Line 4), there is no path in the network that satisfies the request of b slots under the contiguity constraint. If there is no path available then the request is blocked (Line 5). Otherwise, another path to protect the lightpath to be established is searched (Line 7). In case there exists a path, 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 the newly established lightpath. Otherwise, Line 11 transforms the multigraph into $C \times (N - b + 1)$ graphs, considering the spectrum sharing for protecting slots. A path to protect the lightpath to be established should be created (Line 12). In case no path can be created to protect the lightpath then the request is blocked (Line 15). In case a path can be created, the primary path as well as the backup path (Line 17) are established to satisfy the request and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 18 and 19) meaning that the slots were allocated to the newly established lightpath.

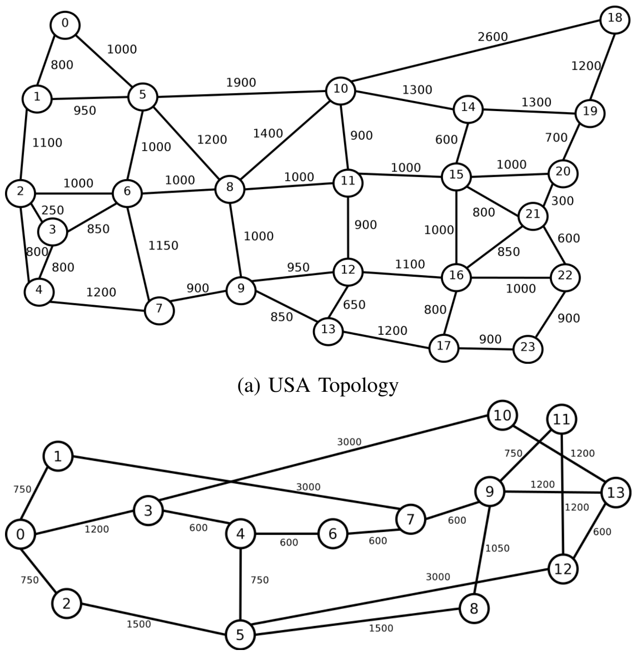
Algorithm 1 SSSPF

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: $\quad\quad$ $(W(T_n), T_n) = \rho(\widetilde{G}_{n,b}, P_n, r(s, d, b))$
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 complexity of the SSSPF algorithm is analyzed as follows. The complexity of transforming the original multigraph in graphs is $O(E + V)$. In the worst case, a shortest straddling p-cycle algorithm is executed in $C \times N - b$ graphs, $O(E + V + (C \times N \times (\|E\| + \|V\| \times log\|V\|)))$, since C and N values can be expressed as constant, then the complexity is: $O(\|E\| + \|V\|log\|V\|)$.

IV. Performance Evaluation

To assess the performance of the SSSPF algorithm in multicore networks, simulation experiments were employed using the FlexGridSim [16] 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. Requests follows a Poisson process 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 16 nodes and 25 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.



(a) USA Topology

(b) NSF Topology

Fig. 2: Topologies

The inter-core crosstalk is a type of interference in which one core causes in 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 [4]. To calculate the crosstalk (XT) from one core in relation to n neighboring cores, in a homogeneous MCF fiber, we used Eq. 1. Considering the coupled-power theory [4] [5], and using Eq. 1 leads to Eq. 2, which was used to ensure the quality of transmission of the connections.

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

Eq. 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.

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

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

We assumed a maximum n value of 6, k = 2×10^{-5}, R = 50 mm, β = 4×10^6 e D = 45 μm [4]. In this study, the worst case of crosstalk is always be the reached 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 the results for networks using the algorithm based on the methods proposed in [10] which uses a K-shortest paths algorithm to compute routes, we use K = 3. The curves labeled "FIPPMC" show the results for networks using the algorithm FIPPMC [7]. The FIPPMC decides on the establishment of lightpaths in an FIPP p-cycle protected network. The curves labeled "MIFMC" show the results for networks using the algorithm MIFMC [8], [9]. 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 "SSSPF" show the results for networks using the proposed algorithm.

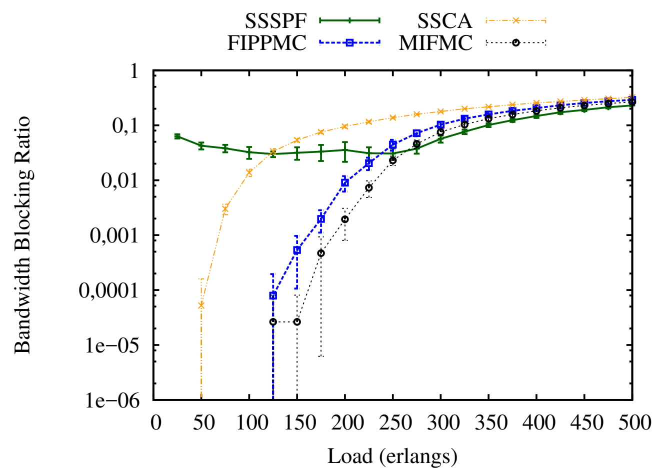


Fig. 3: Bandwidth blocking ratio for the USA topology

Fig. 3 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. While SSSPF starts blocking requests under loads of 25 erlangs, FIPPMC and MIFMC start blocking only under loads of 125 erlangs, and SSCA starts blocking requests under loads of 50 erlangs. The SSSPF algorithm produces the highest BBR, since it produces double protection. SSSPF takes advantage of the high connectivities of nodes in the USA topology and the BBR increases smoothly as a function of the load increase. Under loads of 125 erlangs, the BBR produced by the SSSPF is similar to that produced by the SSCA algorithm, since it does not use spectrum sharing and traffic grooming. Under high loads of 275 erlangs, the BBR values produced by the SSSPF is lower than those produced by the FIPPMC, and similar to those produced by MIFMC. These results show that the SSSPF algorithm produces acceptable blocking for SDM with multi core fibers in despite of protecting two simultaneous failure.

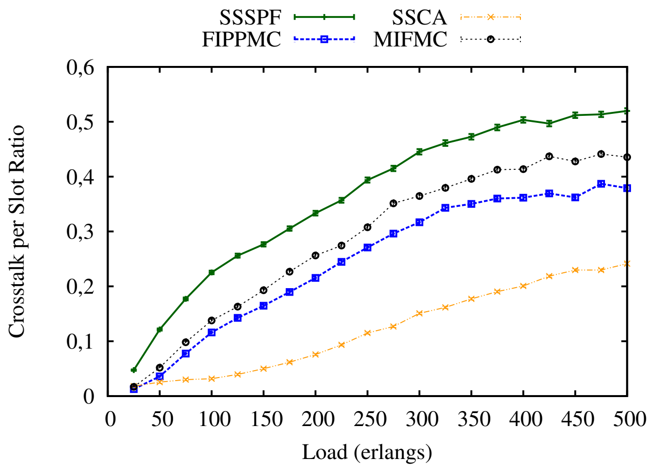


Fig. 4: Crosstalk per slot ratio for the USA topology

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 SSSPF 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 MIFMC algorithm starts at 0.01 and increases until 0.43. The SSSPF algorithm produces the highest CpS values, as a consequence of the high utilization produced. The SSCA algorithm produces the lowest CpS values, as a consequence of the high blocking and low utilization generated.

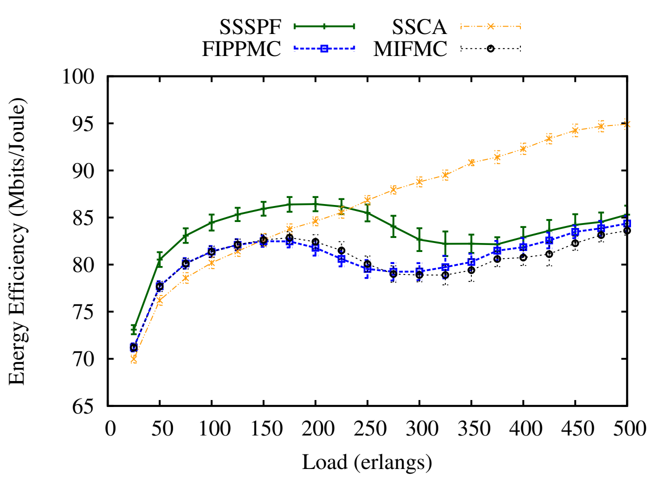


Fig. 5: Energy Efficiency for the USA topology

Fig. 5 shows the energy efficiency as a function of the load for the USA topology. The energy efficiency is obtained by dividing the total traffic demand successfully served in the network by the total power network consumption. The energy efficiency produced by SSSPF is higher than that produced by the FIPPMC and MIFMC algorithms, since it uses spectrum sharing and traffic grooming. There is not much difference between the energy efficiency produced by FIPPMC and that produced by MIFMC. Until 325 erlangs, the energy efficiency produced by the SSSPF algorithm is higher than that produced by the SSCA algorithm.

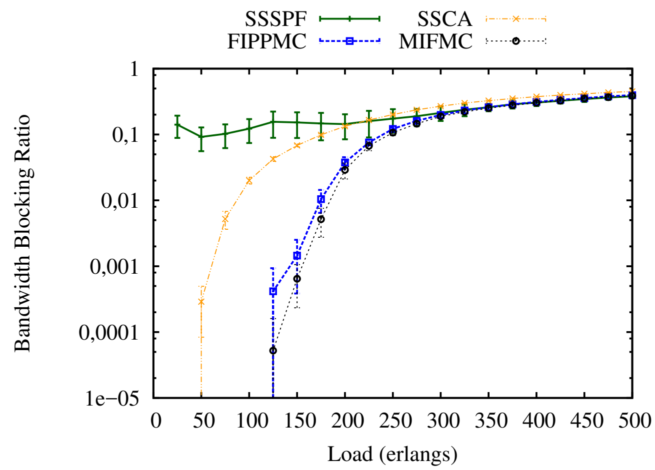


Fig. 6: Bandwidth blocking ratio for the NSF topology

Fig. 6 shows the bandwidth blocking ratio (BBR) as a function of the load for the NSF topology. The SSSPF algorithm starts blocking requests under low load. The highest BBR produced by the SSSPF algorithm is due to the cost of protecting against two simultaneous failures. While FIPPMC and MIFMC start blocking requests under load of 125 erlangs, SSSPF starts blocking only under loads of 25 erlangs. Such trend is a consequence of the FIPPMC and MIFMC algorithms protecting against a single failure only. Under loads of 125 erlangs, the difference between the BBR values produced by the SSSPF algorithm and those given by the FIPPMC and MIFMC algorithms is almost two order and three order of magnitude, respectively. Under high loads of 275 erlangs, the BBR values produced by the SSSPF is similar to the values produced by the other algorithms. The low node degree in this topology leads to the creation of bottlenecks as well as a rapid increase in blocking when compared to the blocking for the USA topology.

Fig. 7 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. The CpS generated by the SSSPF algorithm starts at a 0.06 value and increases until 0.62. The CpS generated by the FIPPMC algorithm starts at a 0.02 value and increases until 0.55. The CpS generated by the MIFMC algorithm starts at a 0.02 value and increases until 0.56. The SSCA 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.

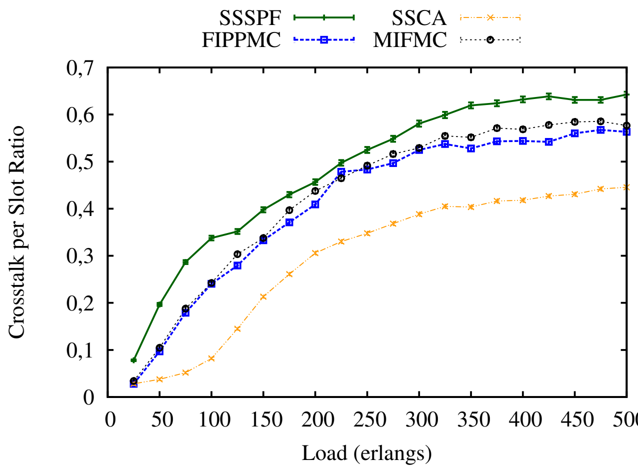


Fig. 7: Crosstalk per slot ratio for the NSF topology

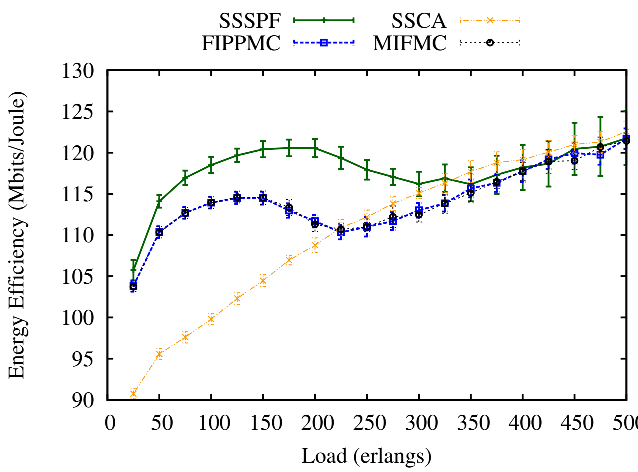


Fig. 8: Energy Efficiency for the NSF topology

Fig. 8 shows the energy efficiency as a function of the load for the NSF topology. The energy efficiency produced by the SSSPF algorithm is the highest one as a consequence of using spectrum sharing and traffic grooming. As for the USA topology, there is not much difference between the energy efficiency produced by FIPPMC and MIFMC algorithms. Until 325 erlangs, the SSSPF algorithm produces energy efficiency higher than does that produced by SSCA algorithm.

V. Conclusion

Protection is a fundamental problem in optical networks, especially in SDM elastic optical networks. This paper focused on the problem of dynamic protection in spacial division multiplexing elastic optical networks mesh networks and proposed a new algorithm called SSSPF to recover from two simultaneous link failures. The SSSPF algorithm provides 100% protection for two failures. Results indicate that the overhead demanded by the SSSPF algorithm is quite acceptable.

Acknowledgments

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