Multipath Routing, Spectrum and Core Allocation in Protected SDM Elastic Optical Networks

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Resumo—The adoption of Space division multiplexing (SDM) in elastic optical networks brings new challenges for spectrum allocation. This paper proposes an algorithm for routing, spectrum and core allocation based on single/multipath routing for providing path protection. The proposed solution has the advantage of using small contiguous bands divided into several paths to provide the request protected bandwidth, allowing the increase in the number of requests accepted. Results show that the proposed algorithm can decrease the blocking ratio by three orders of magnitude when compared with other existing algorithms.

Index Terms—Protection, FIPP p-cycle, Elastic Optical Network, Space Division Multiplexing, Multipath Routing.

I. INTRODUCTION

Elastic Optical Networks (EON) with Space Division Multiplexing (SDM) are a promising solution to handle the increasing demands of bandwidth. The ability to allocate the spectrum in fine granularity will allow this type of network to handle the demands of traffic with diverse bandwidth requirements. In addition, the adoption of space division multiplexing will provide greater capacity availability. The greater the network capacity and the traffic carried, the greater is the need for effective protection schemes to prevent massive loss of data. However, employing backup capacity for path protection reduces resource availability, leading to blocking of incoming requests.

Multipath routing consists in using more than one path to route the bits of a flow. Multipath routing has been used in wavelength division multiplexing to accommodate supra-wavelength bandwidth demands as well as to provide protection to connections [1]. In EON-SDM multipath routing can take advantage of the fine granularity allocation of the spectrum as well as the space dimension, especially when employing multicore fibers. Multipath routing in EON-SDM has also been used as one of the techniques to cope with the problem of the fragmentation of the spectrum [2], [3]. Multipath routing reduces blocking of requests to connection establishment since it uses several paths to provide the bandwidth needed when it is not possible to satisfy the demand with the available bandwidth in a single path.

Different protection schemes can be used to protect paths in optical networks. Shared-backup path protection (SBPP) is one of the techniques which has been extensively investigated,

due to its promotion of efficient sharing of the network capacity [4]. SBPP employs a 1:N protection scheme in which backup paths can use the same path, provided that they use link-disjoint working paths. SBPP defines pre-planned backup paths for disjoint primary paths. Besides the requirements of backup and primary path being disjoint, the backup path should not have common span with other backup paths of any primary path that is not fully disjoint with its own primary path.

This paper proposes an EON-SDM protection algorithm based on SBPP that uses single/multipath routing. We call hybrid routing a policies routing which first tries to allocate a single path for a request and then allocate multiple paths only if the allocation of a single path is not possible. This paper introduces the Multi/singlepath rOuting For multIcOre networks (MOFIO) algorithm for protection provisioning of EON-SDM. Although multipath routing has been used to reduce the spectrum fragmentation in EON-SDM, no previous multipath algorithms has been proposed for the protection of EON-SDM using SBPP. We show that although protection scheme use additional bandwidth to provide protection, multipath routing overperforms single path routing.

The rest of the paper is structured as follow. Section II reviews the 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

Moura and Fonseca, in [5], propose four algorithms for routing, core, modulation level, and spectrum assignment (RCMLSA) based on image processing to search for the available spectrum of multicore fibers at low computational cost. The solutions aim at efficiently utilizing the optical spectrum by considering the crosstalk between the cores of network fibers, as well as by avoiding the allocation of lightpaths that degrade the optical signal.

Hirota *et.al.* [6] divide 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. However, protection is not considered.

Yousef and Rahbar [2] introduced three algorithms to re-solve the fragmentation problem and improve blocking probability in EON-SDM. These algorithms control fragmentation in the cores since they try different ways in order to assign spectrum for a given connection request. However, protection is not considered.

Tan *et.al.* [7] investigate dedicated path protection considering inter-core crosstalk in SDM EONs. The authors use K-shortest-path (KSP) algorithm to obtain a primary path and a backup path. After they solve the problem of inter-core crosstalk between adjacent cores.

An algorithm to dynamically generate primary and backup paths using a shared backup scheme in SDM EONs was proposed in [8]. The algorithm models the spectrum availability in the network as labeled multigraph.

In [9], protection in SDM-EONs including inter-core crosstalk was addressed. The authors introduced three algorithms, designed to provide 100% protection from single failures. The proposed algorithms used different protection schemes to protect the paths.

In [10], the authors investigated the benefits of multipath routing in a environment which includes inter-domain routing in WDM optical networks.

Santi *et. al.*, in [11], applied a multipath routing to serve connection requests with known duration. The authors formulated an optimization model based on Integer Linear Programing (ILP) to leverage multipath routing and grooming in WDM optical networks.

In [12], the potential gains by jointly employing traffic grooming and multipath routing is investigated with a realistic physical impairment model for elastic optical networks.

Ruan *et.al.* [13] study the survivable and multipath problem in elastic optical network. The solution proposed selects multiple routes and allocates spectrum on these routes for a given demand. The papers [12] and [13] do not considered spatial division multiplexing.

To the best of our knowledge, this is the first attempt to consider hybrid routing and shared backup path protection in spatial division multiplexing in elastic optical networks.
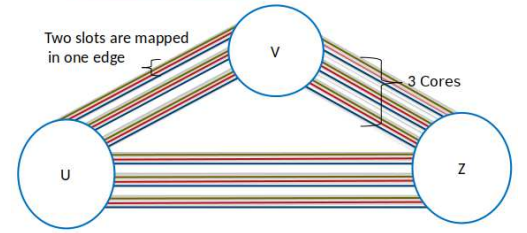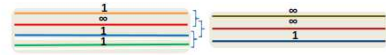
III. THE MOFIO ALGORITHM

The algorithm introduced in this Section, called Multi/singlepath rOuting For multIcOre network (MOFIO), decides on the establishment of lightpaths in protected EON-SDM networks. A lightpath is established if and only if it can be protected by a shared path. In this algorithm, a connection can use either single path or multipath. In both cases, the lightpaths are protected by a shared backup path (SBPP). A multipath is employed in the establishment of a connection in case it is not possibility to establish only a single path for the connection. When a simple path is employed as primary path, a shared backup path is used as the backup path. When multipath is employed, for each primary path a shared path is established for protection. Although shared backup path are shared, under no circumstances the same path can protect more than one path of the same connection. The MOFIO algorithm assures
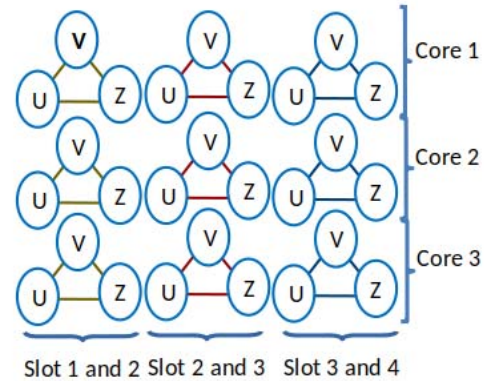
a protection path for each established lightpath against single failures.
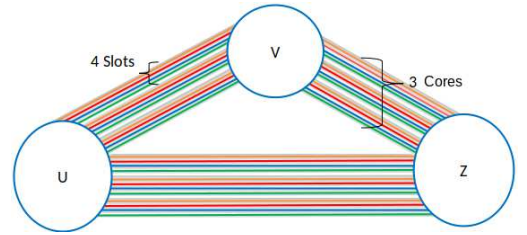
(a) Network with 3 cores and 4 slots.

(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.

Figura 1. Transforming multigraph in graphs

The MOFIO algorithm models the spectrum availability in the network as a labeled multigraph (Fig. 1a). An 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 multigraphs with $N-b+1$ edges (Fig. 1c), with b being the bandwidth demand in slots and N the number of slots in core. 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, with C being the number of cores in a link. Each edge in these graphs represents a combination of b slots. This representation assures spectrum contiguity in the solution. In these graphs, an ∞ value 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.

In the MOFIO algorithm (algorithm 1), Line 1 transforms the multigraph into graphs as described before. Line 2 solves a shortest path algorithm for the graphs. To compute the shortest path the Dijkstra algorithm is executed on all graphs. If it is possible to find a path under the contiguity constraint for the demand b, then a backup path to protect the lightpath to be established is searched (Line 3). In case a path and a protecting SBPP exist, the lightpath is established (Line 5). Otherwise, a backup path to protect the lightpath to be established needs to be created (Lines 7). To compute the backup path the Dijkstra algorithm is executed on all graphs for selecting the shortest backup path. In case the backup path can be created to protect a lightpath, the lightpath as well as the backup path (Lines 9) are established to satisfy the request. Otherwise, a multipath is used (Line 14 to 33). Line 14 transforms the multigraph in graphs considering the division of the bandwidth into k paths. Line 15 solves a k-shortest path algorithm for the graphs and provides the k-paths. To compute the k paths, the Dijkstra algorithm is executed on all graphs, and selecting the k-shortest path. If it is not possible to find k paths under the contiguity constraint for the demand b (line 16), then the request is blocked (line 17). Otherwise, an SBPP to protect each path to be established is searched (Line 19). If there is no SBPP to protect the k path, a backup path to protect the path to be established is created (Line 21). In case it is not possible to create the backup path, the request is blocked. If all backup paths can be created, the lightpath as well as the backup path (Lines 28) are established to satisfy the request.

The complexity of the MOFIO algorithm is analyzed as follows. The complexity of transforming the original multigraph in graphs is $O(E+V)$. Dijkstra complexity is $O(E+V\log V)$. The complexity of the MOFIO algorithm is $O(E+V\log V)$.

IV. Performance Evaluation

To assess the performance of the MOFIO algorithm, simulation was employed using the FlexGridSim [14] and results compared to those given by the SBPPMC [8], CaP-DPP [7] and SSCA [6] algorithms. The CaP-DPP uses a crosstalk-aware provisioning strategy with dedicated path protection whereas SBPPMC algorithm uses shared backup path protection for provide protection. The curves labeled SSCA show the results for networks using the algorithm based in the methods proposed in [7]. In the SSCA algorithm, the primary path is treated independently, i.e., the routing problem and the SCA problem. This approach employs pre-computed multiple routes. The backup path is created in the same way. However, the backup path uses a 1:N scheme. None of these algorithms employ hybrid routing.

Confidence intervals with a 95% confidence level were generated. Each replication simulated 1,00,000 requests. 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. Requests followed a Poisson process and were

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Algorithm 1 MOFIO

Require: $G(V,E), r(s,d,b), k = 2$
Ensure: Primary and Backup paths
1: Transforms the multigraph into C $\times$ (N - b + 1) graphs
2: Computes the shortest path for all graphs
3: **if** $\exists$ Path in the network that satisfies the request **then**
4:     **if** $\exists$ SBPP to protect the path **then**
5:         Accept request $(r(s,d,b))$
6:     **else**
7:         Computes the backup path for all graphs
8:         **if** $\exists$ backup path that satisfies the request **then**
9:             Accept request $(r(s,d,b))$
10:         **end if**
11:     **end if**
12: **end if**
13: **if** The request was not established **then**
14:     Transforms the multigraph into C $\times$ (N -(b/k) + 1) graphs
15:     Computes the k-shortest path for all graphs
16:     **if** $\nexists$ k path that satisfies the request **then**
17:         Block request $(r(s,d,b))$
18:     **end if**
19:     **for all** k path computed **do**
20:         **if** $\nexists$ Established SBPP to protect the path k **then**
21:             Computes the backup path to protect the path k
22:             **if** $\nexists$ backup path to protect the k path **then**
23:                 Block request $(r(s,d,b))$
24:             **end if**
25:         **end if**
26:     **end for**
27:     **if** $\exists$ k paths and k respective backup paths **then**
28:         Accept request $(r(s,d,b))$
29:     **end if**
30: **end if**

uniformly distributed between all pairs of nodes. At least 10 replications were generated for each scenario.

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. The modulation format BPSK was used with 1 bit per symbol. In this paper, BPSK modulation format is employed for extensions of 4000 km with slot capacities of 12.5 Gb/s.

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 [15] [16], and using (1) leads to (2), which was used to ensure the quality of transmission of the connections.
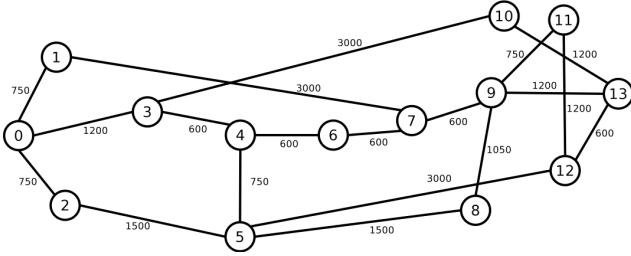
$$h = \frac{2 \cdot k^2 \cdot R}{\beta \cdot D} \tag{1}$$

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.

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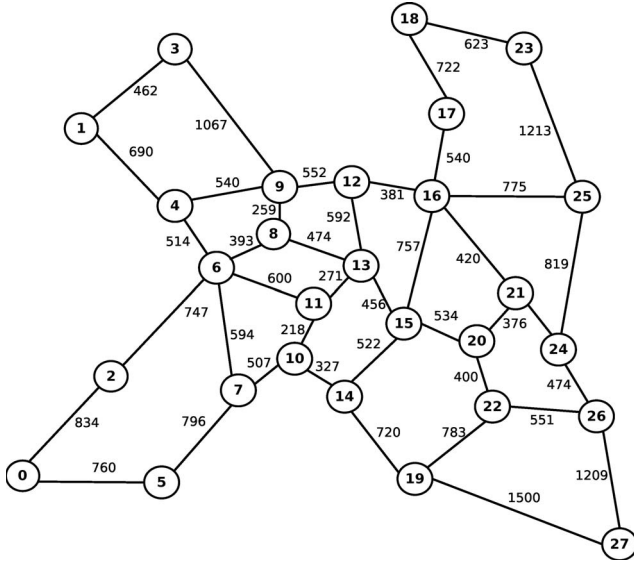
(a) Pan-European Topology

(b) NSF Topology

Figura 2. Topologies

Eq. 2 uses the mean crosstalk increase per unit length (1), the length of the fiber (*L*) and *n* represents the number of neighboring cores. The maximum acceptable crosstalk (XT) values is -16 dB.

The metrics considered to evaluate the algorithms in this paper are Bandwidth Blocking Ratio (BBR), crosstalk per slot (CpS) and Framentation Ratio (FR). BBR is defined as the percentage of bandwidth (traffic) blocked over the total bandwidth requested during the entire simulation period:

$$BBR = \frac{\sum BandwidthBlocked}{\sum TotalBandwidth} \qquad (3)$$

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 (SU) [17]:

$$CpS = \frac{AoC}{SU} \qquad (4)$$

In elastic optical networks, the establishment and tear down of lightpaths leads to the fragmentation of the spectrum which is a state in which there are slots available that cannot be gathered in a way to be used to accept new requests. Fragmentation is generated given the degree which the spectrum

is fragmented from the establishment and the tear-down of paths. The fragmentation ratio compares the maximum number of contiguous slots available (MNCS) to the number of slots available on the link (SAL). The fragmentation ratio is given by:

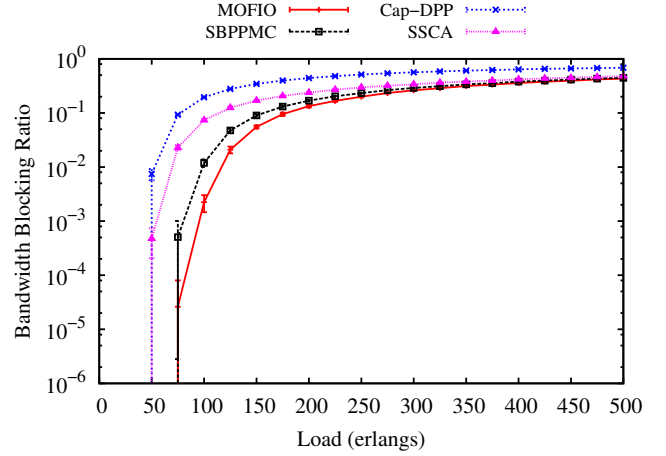$$FR = \frac{MNCS}{SAL} \qquad (5)$$

Figura 3. Bandwidth blocking ratio for Pan-European topology

Fig. 3 shows the bandwidth blocking ratio (BBR) as a function of the load for the Pan-European topology. While Cap-DPP and FIPPMC start blocking requests under loads of 50 erlangs, the MOFIO and SBPPMC algorithms start blocking only under loads of 75 erlangs. Under loads of 75 erlangs, the difference between the BBR produced by the MOFIO algorithm and that given by the SBPPMC, SSCA and Cap-DPP algorithms is one, two and almost three order of magnitude, respectively. Although the difference in BBR between MOFIO and SBPPMC is nearly one orders of magnitude, such difference decreases rapidly under 350 erlangs. The low BBR values produced by the MOFIO algorithm evince the benefits of considering multipath routing when it is not possible to use a single path. The high BBR produced by Cap-DPPM is a consequence of not sharing backup paths. These results show that the MOFIO algorithm produces acceptable blocking for SDM-EON despite the bandwidth reservation for preprovisioning of backup paths.

Figure 4 shows the "Crosstalk per Slot" (CpS) as a function of the load for the Pan-European topology. The generated CpS for the SBPPMC, SSCA and MOFIO algorithms start at a 0.01 value and increases until 0.173, 0.181 and 0.186, respectively. The Cap-DPP algorithm produces lower CpS than the other three algorithms. This happens due to the high blocking generated by this algorithm. Besides the MO-FIO algorithm produces low blocking and high utilization, it produces similar CpS than those produced by the SSCA and SBPPMC algorithms. By using MOFIO, less crosstalk is produced since connection are more uniformly distributed.
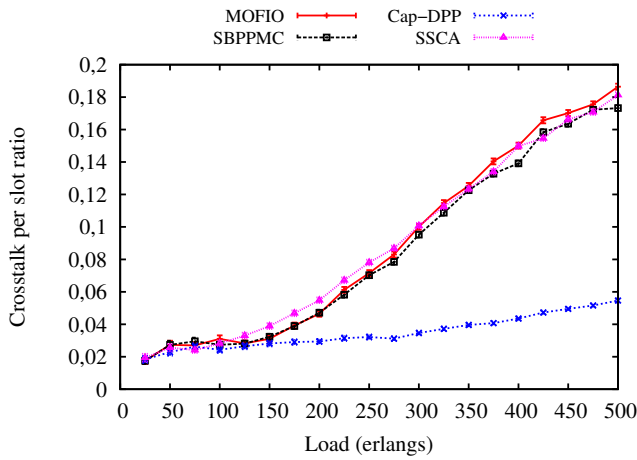
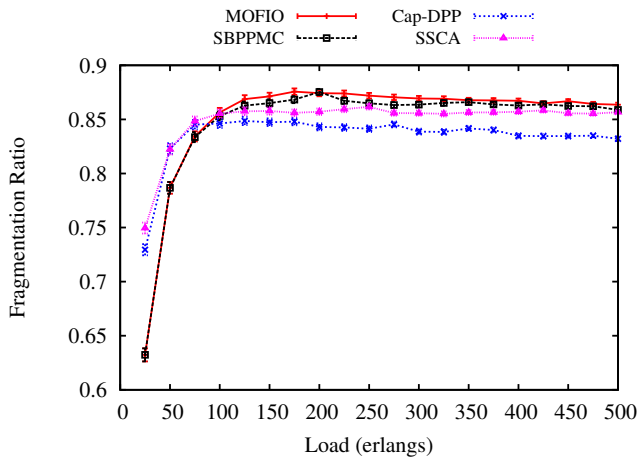Figura 4. Crosstalk per slot ratio for Pan-European topology

Figura 6. Bandwidth blocking ratio for NSF topology

the BBR produced by the MOFIO algorithm and that of the Cap-DPP algorithm is one order of magnitude. This happens due to the low node connectivity in the NSF topology which leads to the creation of bottleneck links.

Figura 5. Fragmentation ratio for Pan-European topology

Figura 7. Crosstalk per slot ratio for NSF topology

Fig. 5 shows the fragmentation ratio as a function of the load for the Pan-European topology. The Cap-DPP algorithm produces a fragmentation ratio almost 10% lower than that given by the SSCA algorithm, as a consequence of using shared backup paths being kept active for longer time and producing less disconnection. Under high loads, the algorithm Cap-DPP produces the lowest fragmentation ratio, as a consequence of the high blocking produced. For the SBPPMC and MOFIO algorithms, the difference in fragmentation ratio exists only for loads greater than 200 erlangs, since only for loads higher than that, there is a need for using multipath routing.

Fig. 6 shows the bandwidth blocking ratio (BBR) as a function of the load for the NSF topology. While Cap-DPP, SSCA and SBPPMC start blocking request for loads of 25, 50 and 150 erlangs, respectively, the MOFIO algorithm starts blocking only for loads of 175 erlangs. For loads of 175 erlangs, the difference between the BBR produced by the MOFIO algorithm and that given by the SBPPMC, SSCA and Cap-DPP algorithms is almost one, three and four order of magnitude, respectively. For loads of 300 erlangs the difference between
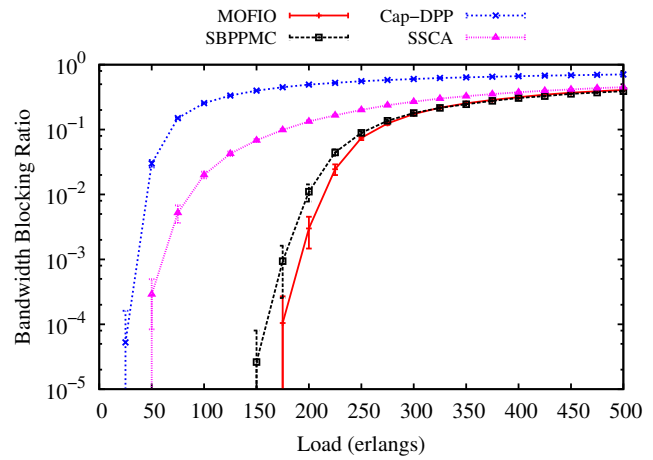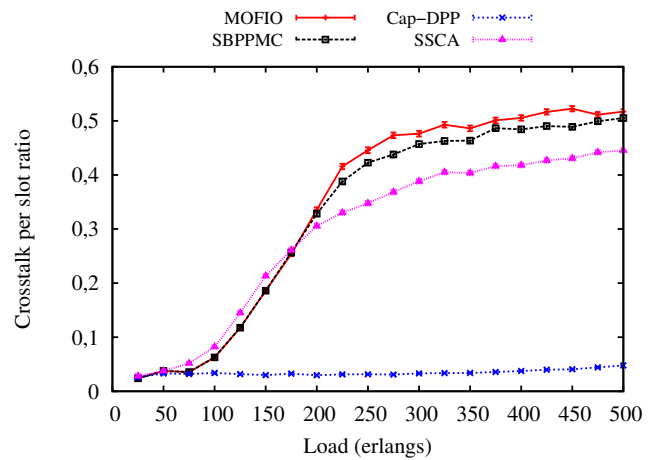
Figure 7 shows the "Crosstalk per Slot" (CpS) as a function of the load for the NSF topology. The generated CpS for the SBPPMC, SSCA and MOFIO algorithms start at a 0.02 value and increases until 0.50, 0.44 and 0.51, respectively. As in Pan-european topology the Cap-DPP algorithm produces lower CpS than the other three algorithms, due to the high blocking generated. Under high loads, the use of MOFIO algorithm leads to CpS values higher than those given by the others algorithms, as a consequence of MOFIO producing low blocking as well as due to the low node connectivity in the NSF topology which leads to the creation of bottleneck links.

Fig. 8 shows the fragmentation ratio as a function of the load for the NSF topology. For this topology, the results are similar to those obtained for the Pan-European topology. Until loads of 200 erlangs SSCA, MOFIO and SBPPMC algorithms produce lower fragmentation ratio than does the CaP-DPP algorithm,
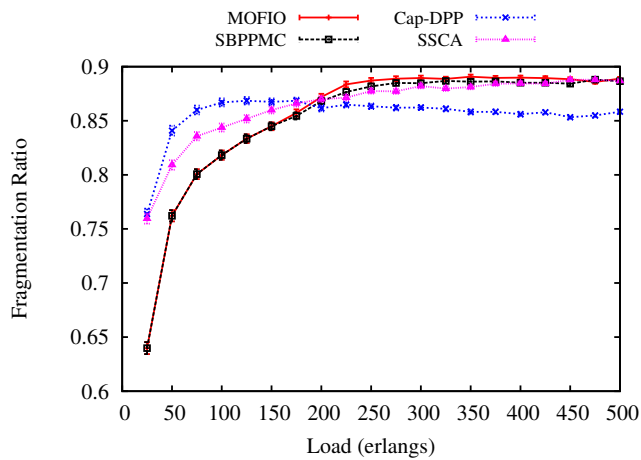
Figura 8. Fragmentation ratio for NSF topology

as a consequence of shared backup paths being kept active for long time and producing less disconnection. The SBPPMC and the MOFIO algorithms produce similar fragmentation ratio values close to those generated by SSCA. Although using multipath routing, under high loads, the MOFIO algorithm produces the highest fragmentation ratio, due the low blocking produced by this algorithm.

V. Conclusions

Protection is a fundamental aspect in optical networks, especially in SDM elastic optical networks in which traffic is concentrated on only a few links, which increases the damage caused by a single failure. This paper has introduced an algorithms to support the establishment of lightpaths in spacial division multiplexing elastic optical networks protected by shared backup path protection by using multipath routing. The MOFIO algorithm provides 100% protection against single failures. Simulation results evince the lower blocking produced by the MOFIO algorithm when compared to those produced by the other single path algorithms which evidences the advantage of employing hybrid routing for EON-SDM. The paper is the first to investigate the advantage of multipath routing in EON-SDM protected. As future work, hybrid algorithms based on different protection shemes should be developed for the assignment and comparison of the advantages of using multipath routing for providing protection by EON-SDM.

Acknowledgments

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