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Routing, spectrum and core assignment algorithms for protection of space division multiplexing elastic optical networks

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ABSTRACT

Protection is a key issue in optical networks, mainly in spacial division multiplexing (SDM) elastic optical networks (EONs) as these handle the increasing amount of heterogeneous Internet traffic. In this paper, we address protection in SDM-EONs including inter-core crosstalk. We introduce three algorithms, designed to provide 100% protection from single failures. Extensive simulation is used to show that the proposed algorithms prevents the formation of network bottlenecks, thus maintaining the protection of the connections.

1. Introduction

The development of multi-core fiber technology has led to the adoption of spacial division multiplexing (SDM) in elastic optical networks (EONs). SDM introduces the use of multiple cores in parallel, which leads to an n-fold increase in capacity (Siracusa et al., 2015; Klinkowski et al., 2018). Various type of fiber can be employed: multi-mode fibers (MMF), multi-core fibers (MCF) and few-mode multi-core fiber. With MMF, the number of modes supported by a single fiber depends on the core size and the refraction index of the fiber cladding. In MCF, however, each core acts as a single mode fiber. These MCFs are considered here, as they present the advantages of lower crosstalk, core independence and a high cost benefit relationship.

One of the fundamental problems in EON is the routing and spectrum assignment (RSA) problem which must consider contiguous and continuous allocation of the spectrum for all links of a lightpath (Fujii et al., 2014; Chatterjee et al., 2016; Ricciardi et al., 2015). The inclusion of the degree of freedom of space adds another dimension to the traditional RSA problem, which then becomes the routing, spectrum and core allocation (RSCA) problem. When considering MCF, the RSCA formulation must also consider the crosstalk produced by propagation in the same band of the spectrum in adjacent cores.

Although various RSCA algorithms for spectrum allocation have been proposed (Tode and Hirota, 2014; Yin et al., 2013; Fujii et al., 2014; Proietti et al., 2015; Muhammad et al., 2014; Rumipamba-Zambrano et al., 2018), only (Tan et al., 2016) has addressed the protection of lightpaths. Optical transport networks carry huge amounts of traffic, and with the capacity increase arising from the use of MCF, any disruption in transmission implies much greater loss of data. Consequently, RSCA algorithms to provide path protection in SDM-EON need to be developed so these networks, can operate properly.

Different protection schemes can be used to protect the paths in optical networks. Shared-backup path protection (SBPP) is one of techniques which has been extensively investigated, due to its promotion of efficient sharing of the network capacity (Guo et al., 2016, 2017; Shen et al., 2014). SBPP employs a 1:N protection scheme in which backup paths can use the same path, provided that they use corresponding link-disjoint working paths.

Most of the protection techniques reserve backup resources but do not pre-configure, which, however, may result in a long signaling procedure during path restoration (Chen et al., 2015) after a link failure. p-cycle is a protection technique with pre-configured backup resources which can protect the on-cycle spans, as well as straddling spans. They combine the advantage of mesh networks with the restoration speed of ring networks (Asthana et al., 2010). One special case of p-cycles for path protection is the so called failure-independent path protecting p-cycles (FIPP). FIPP p-cycles furnish protection for end-to-end working (primary) paths with end nodes on the p-cycle. FIPP is an extension of the p-cycle concept in which failure is not limited to the link or path segment immediately adjacent to the end nodes. FIPP p-cycles offer all the advantages of SBPP as well as pre-configuration of the protection path. The problem of using FIPP p-cycles is the large number of resource needed for the creation of the cycle. FIPP p-cycles have been studied for the protection of EONs (Chen et al., 2015; Oliveira and da Fonseca, 2014; Wei et al., 2015). However, few previous studies have

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shown their use for the protection of spacial division multiplexing elastic optical network (SDM-EON) (Tan et al., 2016; Oliveira and da Fonseca, 2016a; Oliveira and da Fonseca, 2016b; Oliveira and da Fonseca, 2016a; Oliveira and da Fonseca, 2017a).

Traditional protection schemes can lead to a rapid consumption of network resources, due to unbalanced utilization of network links which motivates the design algorithms employing minimum interference routing that suggests the use of paths to reduce the chances of blocking of incoming requests for connection establishment (Oliveira and da Fonseca, 2017b). Since p-cycles can be formed using the same links used by primary paths, their employment for protection can lead to the exhaustion of resources. One approach for decreasing the rejection of future requests is to generate straddling p-cycles as these prevent p-cycles sharing links with primary paths.

The contribution of this paper is the introduction of three novel RSCA algorithms for path protection against single failure in elastic optical networks with spacial division multiplexing. All three algorithms employ a Routing and Spectrum Assignment algorithm based on a multigraph representation of the spectrum. The Shared Backup Path Protection for MultiCore networks algorithm (SBPPMC) algorithm employs shared backup paths to protect primary paths. The Failure-Independent Path Protection for MultiCore networks algorithm (FIPPMC) employs failure independent path protection (FIPP) p-cycles to protect primary paths. The Minimum Interference and Failure-independent path protection for MultiCore networks algorithm (MIFMC) uses a FIPP p-cycle that prioritizes the use of straddling p-cycles as a criterion for minimum interference routing. The results obtained here extend those found in preliminary investigations (Oliveira and da Fonseca, 2017b; Oliveira and da Fonseca, 2016b; Oliveira and da Fonseca, 2016a).

The rest of this paper is structured as follow. Section 2 presents related work on elastic optical network protection and spacial division multiplexing elastic optical networks. Section 3 presents the model used to represent inter-core crosstalk. Section 4 introduces the proposed algorithms. Section 5 evaluates the performance of these algorithms. Finally, Section 6 presents the conclusions.

2. Related work

2.1. Routing, spectrum and core allocation

Only recently have routing, spectrum and core allocation solutions have been proposed and some of these proposal are summarized here.

An adaptive routing and spectrum allocation algorithm for elastic optical networks based on sequential search (sequential fitting) and adaptive routing was proposed in Alyatama et al. (2017). The algorithm used the history of established connections to identify the near-optimal allocation of the optical spectrum.

Hirota et al. (Tode and Hirota, 2014) divided the RSCA problem into two separate problems: the routing problem and the spectrum and core allocation problem. A K-shortest path algorithm is used for the routing solution. The algorithm is crosstalk aware and employs prioritization for spectrum and core allocation.

The authors in Moura and da Fonseca (2016) incorporate the connected component labeling (CCL) algorithm, a fundamental algorithm in pattern analysis of digital images, in the solution of the RSCA problem. By using the CCL algorithm, the RSCA algorithm can look for regions of the spectrum with low computational complexity. The use of connected regions guarantees the contiguity constraint in the spectrum. The algorithm identifies all the connected regions of slots to decide in which to accommodate a connection. Moreover, spectrum fitting policies are proposed to help make this decision.

In Muhammad et al. (2014), a routing, spectrum and core allocation (RSCA) solution is proposed for the network planning problem using an integer linear programming (ILP) formulation, as well a heuristic algorithm. The aim was to minimize the number of spectrum slices required on any core of a multi-core fiber in a SDM-EON.

Table 1
Comparison of related papers.

Approach	Protection	SDM	RCSA	Sharing
Tode and Hirota (2014)	No	Yes	Yes	No
Muhammad et al. (2014)	No	Yes	Yes	No
Chen et al. (2015)	Yes	No	No	Yes
Oliveira and da Fonseca (2014)	Yes	No	No	Yes
Wei et al. (2015)	Yes	No	No	Yes
Moura and da Fonseca (2016)	No	Yes	Yes	No
Zhu et al. (2016a)	No	Yes	Yes	No
Walkowiak and Klinkowski (2013)	Yes	No	No	No
Yin et al. (2017)	Yes	No	No	No
Oliveira and da Fonseca (2016c)	Yes	No	No	Yes
Oliveira et al. (2015)	Yes	No	No	No
Zhu et al. (2016b)	Yes	No	No	Yes
Tan et al. (2016)	Yes	Yes	Yes	No
FIPPMC	Yes	Yes	Yes	Yes
SBPPMC	Yes	Yes	Yes	Yes
MIFMC	Yes	Yes	Yes	Yes

The authors in Zhu et al. (2016a) proposed of RSCA algorithms designed for advanced immediate reservation requests in SDM-EONs employing multi-core fibers (MCFs). They proposed a metric, multi-dimensional resource compactness, to measure the spectrum fragmentation.

2.2. Protection

Protection schemes for optical networks have been extensively studied (Walkowiak and Klinkowski, 2013; Yin et al., 2017; Asthana et al., 2010; Oliveira and da Fonseca, 2014; Oliveira and da Fonseca, 2016c; Oliveira et al., 2015; Guo et al., 2017; Guo et al., 2016; Shen et al., 2014; Wei et al., 2015; Chen et al., 2015; Zhu et al., 2016b; Walkowiak et al., 2014). The work in Tan et al. (2016) considered protection in elastic optical networks employing spacial division multiplexing and introduced a crosstalk-aware provisioning strategy with dedicated path protection. The algorithm proposed was divided into routing computation and core and spectrum allocation. A K-shortest-path (KSP) algorithm was employed to find paired primary and backup paths.

Khodashenas et al. (Walkowiak and Klinkowski, 2013) proposed offline routing and spectrum assignment (RSA) algorithms for a survivable elastic optical network scenario employing shared backup path protection (SBPP). The algorithms were based on an Integer Linear Programming (ILP) formulation.

Various papers have investigated the employment of FIPP-p-cycles for protection of elastic optical networks (Oliveira and da Fonseca, 2014; Chen et al., 2015; Zhu et al., 2016b; Oliveira and da Fonseca, 2016c). In Oliveira and da Fonseca (2016c), the use of p-cycle, traffic grooming and spectrum overlap to provide path protection are explored. The work in Zhu et al. (2016b) focused on the efficient use of the spectrum in the face of spectrum reservation to provide protection.

Table 1 compares the algorithms described in this paper to various others described in the literature in relation to the provisioning of protection, the use of spacial division multiplexing, the employment of a routing, spectrum and core allocation algorithm, and resource sharing for protection provisioning. The RSCA algorithms introduced in the present paper is unique in that it adopts crosstalk aware allocation decisions based on a multigraph representation of the spectrum.

3. Inter-core crosstalk

The flexibly of fine granularity in the allocation of the spectrum facilitates the handling of heterogeneous traffic demands efficiently. However, the use of multiple cores generates inter-core crosstalk (XT),

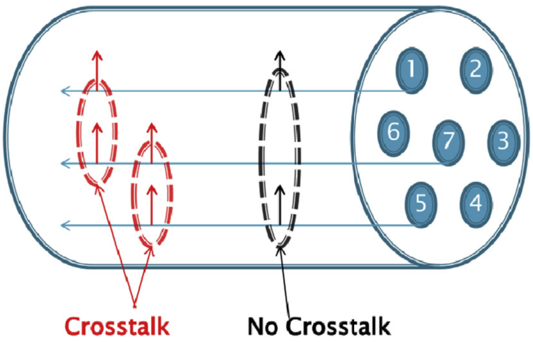


Fig. 1. Inter-core crosstalk.

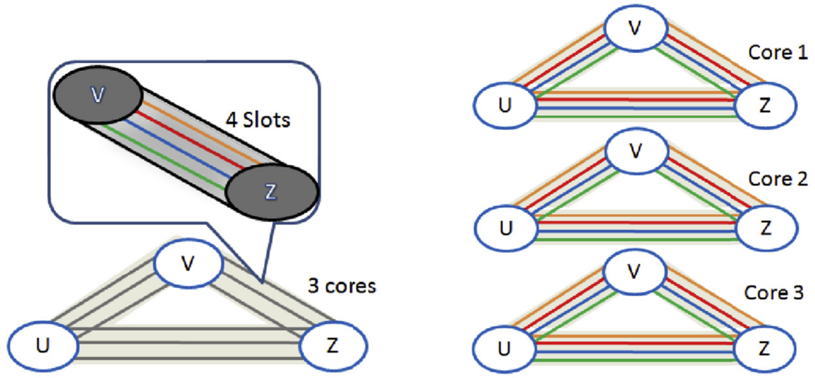
which impacts the quality of transmission and reduces the availability of the spectrum for future allocations.

The inter-core crosstalk is a type of interference, which adjacent cores cause to another along the same optical fiber link. It can be defined as the optical power added by adjacent links to the power of a signal in a core divided by the power in that core, measured in dB. Fig. 1 illustrates a multicore fiber. In this figure, if the cores 5 and the core 7 use the same spectrum slots, inter-core crosstalk happens since the core 7 and the core 5 are adjacent, which does not occur when cores 1 and 5 use the same spectrum slots since they are not adjacent.

RSCA algorithms must therefore assure that the condition of the spectrum allocated to a connection will be adequate so that the signal transmitted can be decoded at the destination. Therefore, before allocating a region of a spectrum to a connection, the level of crosstalk in this region needs to be checked. If it is above an unacceptable threshold value, the region should not be allocated. Moreover, even if the crosstalk level is below the threshold value, an evolution must be made of the impact of the crosstalk generated by the incoming connection on the crosstalk of all connections. If this crosstalk will exceed the threshold, the connection should not be accepted, since the quality of transmission in already established connections will be degraded.

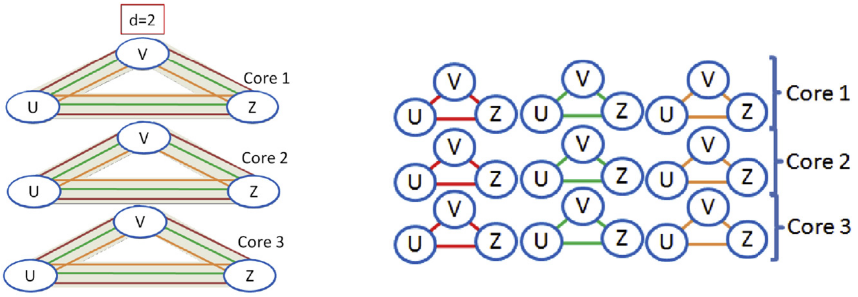
Table 2
Notation.

s: source node;
d: destination node;
b: bandwidth demand;
N: number of slot between two nodes;
C: number of cores;
V: set of nodes;
$e_{u,v,n}$: the nth 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 of a set of nodes V, a set of edges E and a set of edge weight W, $|E| = C \cdot N \cdot F$.
$r(s, d, b)$: request from the node s to the node d with bandwidth demand b;
$\chi(r(s, d, b))$: blocks request;
$\Upsilon(r(s, d, b))$: establishes request;
$\delta(G, r(s, d, b))$: shortest path between s and d in G that satisfies the request for b slots;
$w(e_{u,v,n})$: weight of the edge $e_{u,v,n}$; $w(e_{u,v,n}) < \infty$ if the nth slot in the link connecting OXC u and v is free, $w(e_{u,v,n}) = \infty$ 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 $\widetilde{e_{\widetilde{u},\widetilde{v}}}$ in graph n; $\widetilde{w}_n(\widetilde{e_{\widetilde{u},\widetilde{v}}}) < \infty$ if the corresponding edges in the graph are free and can be used without generating unacceptable XT for a modulation m; $w(e_{u,v,n}) = \infty$ if the slot is already allocated or if it generates unacceptable XT;
$\widetilde{W} = \widetilde{w}_n(\widetilde{e_{\widetilde{u},\widetilde{v}}})$;
$\widetilde{G}_{n,b} = (\widetilde{V}, \widetilde{E}, \widetilde{W})$: the nth 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 with $\widetilde{E}$. 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;
$W(p_n)$: $\sum_{\widetilde{e_{\widetilde{u},\widetilde{v}}} \in \{p_n\}} \widetilde{e_{\widetilde{u},\widetilde{v}}}$: 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;
t_n: p-cycle containing the nodes u and v, edges corresponding to the mapping of the b edges of the multigraph G;
$T = \{t_n\}$: set of all established p-cycles;
P_{t_n}: set of all paths protected by p-cycle t_n;
$W(t_n)$: $\sum_{\widetilde{e_{\widetilde{u},\widetilde{v}}} \in \{t_n\}} \widetilde{e_{\widetilde{u},\widetilde{v}}}$: weight of the p-cycle t_n (the sum of the weights of all the edges);
$W_{t_{s,d}}$ = the weight of the p-cycle that will protect the path between s and d;
$\xi(\widetilde{G}_{n,b}, p_n, r(s, d, b))$: shortest p-cycle t_n, between s and d in $\widetilde{G}_{n,b}$, that P_{t_n} are paths disjoint to p_n, and that the p-cycle satisfies the request of bandwidth b;
$\mu(p_n, T, r(s, d, b))$: p-cycle in T that P_{t_n} are paths disjoint to p_n and satisfies the request of bandwidth b;
$\vartheta(\widetilde{G}_{n,b}, p_n, r(s, d, b))$: p-cycle t_n, between s and d in $\widetilde{G}_{n,b}$, satisfies the request of bandwidth b, that it is disjoint to p_n (p-cycle straddling to p_n) and that P_{t_n} are paths disjoint to p_n;
z_n: backup path containing the nodes u and v, and edges corresponding to the mapping of the b edges of the multigraph G;
$Z = \{Z_n\}$:set of all established backup paths;
P_{z_n}: set of all paths protected by backup path z_n;
$W(z_n)$: $\sum_{\widetilde{e_{\widetilde{u},\widetilde{v}}} \in \{z_n\}} \widetilde{e_{\widetilde{u},\widetilde{v}}}$: the weight of the backup path z_n (the sum of the weights of all the edges);
$W_{z_{s,d}}$ = weight of the backup path which protects the path between s and d;
$\nu(p_n, Z, r(s, d, b))$: shortest path in Z that P_{z_n} are link disjoint to p_n and satisfies the request of bandwidth b;
$\phi(\widetilde{G}_{n,b}, p_n, r(s, d, b))$: backup path in z_n between s and d, that z_n and P_{z_n} are link disjoint to p_n, and satisfies the request of bandwidth b;



(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. 2. Transforming multigraph in graphs.

To calculate the crosstalk (XT) from one core in relation to n neighboring cores, in a homogeneous MCF fiber, we used Eq. (1).

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

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

Where:
h is crosstalk increase per unit length;
k is the coupling coefficient;
β propagation constant;
R bend radius of fiber;
D core-pitch (distance between cores)
L is the length of the fiber;
n is the number of adjacent cores;

In this paper, we make the same realistic assumptions assumed in Saridis et al. (2015): $k = 2\times 10^{-5}$, $R = 50\,\text{mm}$, $\beta = 4\times 10^{6}$ e $D = 45\,\mu\text{m}$.

4. Proposed algorithms

This section introduces the FIPPMC, SBPPMC and MIFMC algorithms, as well as a representation of their use of the spectrum. The mathematical notations used is summarized in Table 2.

The proposed algorithms model the spectrum availability as a labeled multigraph (Fig. 2(a)). A label on an edge represents the availability of a slot. In Fig. 2(b), the multigraph is divided into C multigraphs, where C is the number of cores. Each of these multigraphs is transformed into further multigraphs with $N - b + 1$ edges, (Fig. 2(c)) where b is the bandwidth demand on the basis of the modulation format chosen. Each of these multigraphs is then transformed into $N - b + 1$ graphs. In other words, the original multigraph (Fig. 2(c)) is transformed into $C \times (N - b + 1)$ graphs (Fig. 2(d)) with edge in these graphs representing a combination of b slots. This representation assures spectrum contiguity in the solution. Labels on the edges of these graphs represent the availability of the slots for allocation. A slot is unavailable either if it is already allocated or if the crosstalk value on the slot is unacceptable for a successful transmission. In this paper, a crosstalk value greater than $-16\,\text{dB}$ is considered acceptable.

4.1. FIPPMC algorithm

The first algorithm introduced is the Failure-Independent Path Protecting for MultiCore networks (FIPPMC) algorithm, which employs FIPP p-cycles 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 primary paths.

Requests for the establishment of lightpaths arrive dynamically, and for each request an existing p-cycle is sought. If no existing p-cycle already protects the potential lightpath, then another path is sought to create a new FIPP p-cycle for the request. If no FIPP p-cycle can be created that will protect the lightpath, then the request connection is not established.

Algorithm 1 FIPPMC.

```
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:       $W_{p_{s,d}} = W(p_n) \mid \ \forall i \ W(p_n) \le W(p_i)$
4: if $W_{p_{s,d}} = \infty$ then
5:    $\chi(r(s,d,b))$
6: else
7:    if $\exists \mu(p_n, T, r(s,d,b))$ then
8:       $\Upsilon(r(s,d,b))$ as $p_n$ and $t_n$
9:       $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in p_i$
10:   else
11:      $(W(t_n), t_n) = \xi\ (\widetilde{G}_{n,b}, p_n, r(s,d,b)) \quad \forall n \in \sigma$
12:      $W_{t_{s,d}} = W(t_n) \mid \ \forall i \ W(t_n) \le W(t_i)$
13:      if $W_{t_{s,d}} = \infty$ then
14:         $\chi(r(s,d,b))$
15:      else
16:         $\Upsilon(r(s,d,b))$ as $p_n$ and $t_n$
17:         $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in p_i$
18:         $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in t_i$
19:      end if
20:   end if
21: end if
```

The FIPPMC algorithm is introduced as Algorithm 1. Line 1 transforms the multigraph into $C \times (N - b + 1)$ graphs. Line 2 computes the shortest path for every graph $\widetilde{G}_{n,b}$ and chooses the one that costs the least. Line 3 selects the path among all shortest paths that has the lowest cost. In case the weight of all shortest paths is ∞ (Line 4), there is no path in the network that satisfies the bandwidth request under the contiguity constraint, and the request will be blocked (Line 5). Otherwise, a p-cycle to protect this lightpath to be established is sought (Line 7). In case such a p-cycle exists, 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 have been allocated to the newly established lightpath. Otherwise, a p-cycle to protect the lightpath to be established should be created (Line 11). If no p-cycle can be created to protect the lightpath, then the request is blocked (Line 14). Otherwise, the primary path, as well as the p-cycle (Line 16), are established to satisfy the request, and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 17 and 18), meaning that the slots were allocated to the newly established lightpath.

The complexity of the FIPPMC algorithm is analyzed as follows. The complexity of transforming the original multigraph into σ graphs is $O(E + V)$. For the primary path, in the worst case, Dijkstra's algorithm is executed on $C \times (N - b)$ graphs.

For the p-cycle, in the worst case, Suurballe's algorithm (Bhandari, 1999) is executed for the $C \times (N - b)$ graphs, for each path that forms the p-cycle. Given that the complexity of Dijkstra's algorithm is $O(\|E\| + \|V\| \log \|V\|)$ and the complexity of Suurballe's algorithm is $O(\|E\| + \|V\| \log \|V\|)$ and that C and N are constant values, the complexity of the FIPPMC algorithm is: $O(\|E\| + \|V\| \log \|V\|)$.

4.2. SBPPMC algorithm

The second algorithm to be introduced here is the Shared Backup Path Protection for MultiCore network (SBPPMC) algorithm, it decides on the establishment of lightpaths if and only if these can be protected by a shared backup path. The SBPPMC algorithm uses backup paths interleaved with primary paths, in order to generate less crosstalk per slot.

Algorithm 2 SBPPMC.

```
7:    if $\exists \nu(p_n, Z, r(s,d,b))$ then
11: $(W(z_n), z_n) = \phi(\widetilde{G}_{n,b}, p_n, r(s,d,b)) \quad \forall n \in \sigma$
12: $W_{z_{s,d}} = W(z_n) \mid \ \forall i \ W(z_n) \le W(z_i)$
```

The SBPPMC algorithm differs from the FIPPMC one by considering a shared backup path for protection rather than using a FIPP p-cycle. The process of creating primary and backup paths in the SBPPMC algorithm is similar to that used in the FIPPMC algorithm. The SBPPMC algorithm is introduced as Algorithm 2. Lines 1 to 6 of the SBPPMC algorithm are the same to those as in the FIPPMC algorithms, these lines create the primary path. In the SBPPMC algorithm, however, Lines 7, 11 and 12 create a shared backup path rather than an FIPP p-cycle.

The derivation of complexity of the SBPPMC algorithm is analyzed as follows. The complexity of transforming the original multigraph to σ graphs is $O(E + V)$. For primary and backup path, Dijkstra's algorithm is used for the $C \times (N - b)$ graphs. In the worst case scenario, Dijkstra's algorithm is executed on $2 \times C \times (N - b)$ graphs. Since C and N represent constant values, the complexity is $O(\|E\| + \|V\| \log \|V\|)$.

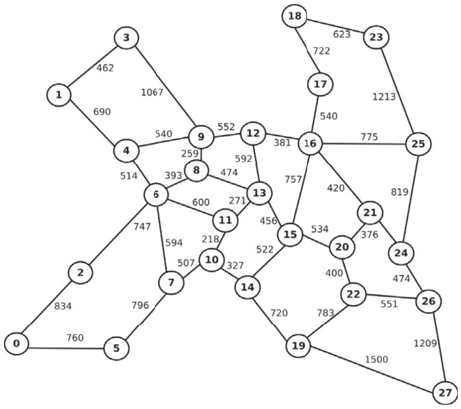
4.3. MIFMC algorithm

The third algorithm is the Minimum Interference and Failure-independent path protection for MultiCore networks (MIFMC) algorithm establishes lightpaths if and only if these can be protected by an FIPP p-cycle with both on-cycle and straddling paths.

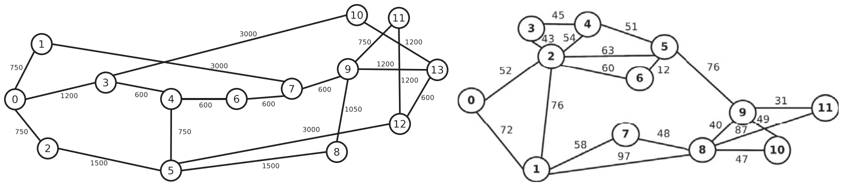
Algorithm 3 MIFMC.

```
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:       $W_{p_{s,d}} = W(p_n) \mid \ \forall i \ W(p_n) \le W(p_i)$
4: if $W_{p_{s,d}} = \infty$ then
5:    $\chi(r(s,d,b))$
6: else
7:    if $\exists \mu(p_n, T, r(s,d,b))$ then
8:       $\Upsilon(r(s,d,b))$ as $p_n$ and $t_{s,d}$
9:       $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in p_i$
10:   else
11:      $(W(t_n), t_n) = \vartheta\ (\widetilde{G}_{n,b}, p_n, r(s,d,b)) \quad \forall n \in \sigma$
12:      $W_{t_{s,d}} = W(t_n) \mid \ \forall i \ W(t_n) \le W(t_i)$
13:      if $W_{t_{s,d}} = \infty$ then
14:
        $(W(t_n), t_n) = \xi\ (\widetilde{G}_{n,b}, p_n, r(s,d,b)) \quad \forall n \in \sigma$
15:         $W_{t_{s,d}} = W(t_n) \mid \ \forall i \ W(t_n) \le W(t_i)$
16:         if $W_{t_{s,d}} = \infty$ then
17:            $\chi(r(s,d,b))$
18:         else
19:            $\Upsilon(r(s,d,b))$ as $p_n$ and $t_n$
20:            $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in p_i$
21:            $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in t_i$
22:         end if
23:      else
24:         $\Upsilon(r(s,d,b))$ as $p_n$ and $t_n$
25:         $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in p_i$
26:         $W(\widetilde{e}_{u,v,i}) = \infty \quad \forall \{u,v\} \in t_i$
27:      else if
28:   else if
29: end if
```

The reservation of resources to create protective on-cycle FIPP p-cycle paths can exhaust the resources of networks links. Thus, it is necessary to avoid the formation of network bottleneck links, as this will increases the blocking of incoming requests. The approach adopted by



(a) Pan-European (b) USA



(c) NSF (d) Cesnet

Fig. 3. Topologies used in the simulations.

the MIFMC algorithm to achieve such a balance is to priorize the use of straddling p-cycles to protect the primary path.

The MIFMC algorithm is introduced in Algorithm 3. As in the FIPPMC algorithm, Lines 1 to 5 represent the creation of the primary path. If a primary path is available, a p-cycle to protect this lightpath is sought (Line 7). The search for such a p-cycle (Lines 7 to 10) is the same as in the FIPPMC algorithm. If there is no such p-cycle, one must be created to protect the lightpath to be established (Line 11). The difference between the FIPPMC and MIFMC is in the creation of p-cycles. Unlike the FIPPMC algorithm, MIFMC attempts to create a minimal interference p-cycle and establish both the path and p-cycle (lines 19 through 21). If the p-cycle with minimal interference can not be created (line 13), an on-cycle p-cycle needs to be created (line 14). If an on-cycle p-cycle cannot be created (line 16), the request is blocked. Otherwise, the primary path as well as the backup path are established to satisfy the request and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 24 to 26).

The complexity of the MIFMC algorithm is the same as that of the FIPPMC algorithm, since the creation of lightpaths and backup paths are very similar and employ both the Dijkstra and Suurballe algorithms.

5. Performance evaluation

To assess the performance of the proposed algorithms in multicore networks, simulation experiments were conducted employing the FlexGridSim (Moura and Drummond). Connection requests were uniformly distributed among all pair of nodes in the network. The network load was varied from 25 to 500 erlangs, and each simulation involved 100,000 connection requests. Confidence intervals were derived using the independent replication method, and a 95% confidence level was adopted. Requests followed a Poisson process and were uniformly-distributed between all pairs of nodes. At least 10 replications were generated for each scenario.

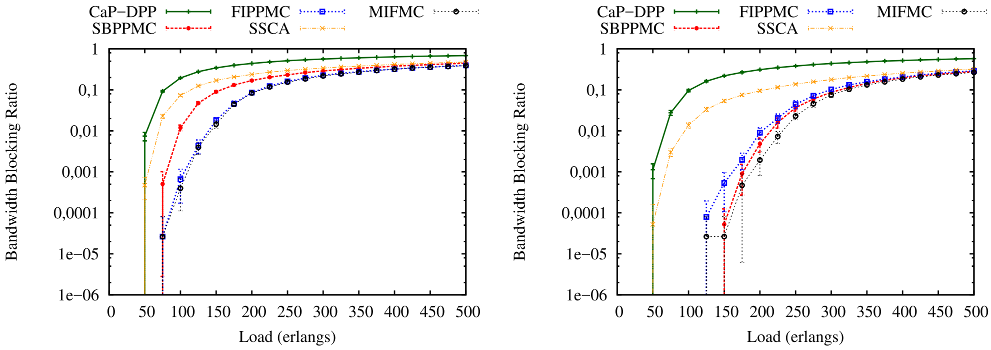
Simulations of the different algorithms used the same set of seeds. Seven types of requests were employed 25 Gbps, 50 Gbps, 125 Gbps, 200 Gbps, 500 Gbps, 750 Gbps and 1 Tbps. The links were composed of MCFs with 7 cores and each core was divided in 320 slots. The topologies used in the simulations were the Pan-Europan (Fig. 3(a)), the USA (Fig. 3(b)), the NSF (Fig. 3(c)) and the Cesnet (Fig. 3(d)) topologies. The Pan-Europan topology has 28 nodes and 82 links, the USA topology has 24 nodes and 43 links, the NSF topology has 16 nodes and 25 links and the Cesnet topology has 12 nodes and 19 links. The numbers on the links represent the length of the link in kilometers.

The bandwidth blocking ratio, the crosstalk per slot, the fragmentation ratio and energy efficiency were assessed in the simulations. The bandwidth blocking ratio is the percentage of the blocked traffic in relation to the total bandwidth requested during each simulation. The crosstalk per slot is the average ratio between slots being affected by crosstalk and the total number of slots used in a link. (Fujii et al., 2014). In spacial division multiplexing 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 available slots, that cannot be gathered for use to accept new requests. The fragmentation ratio is defined as the average ratio between the number of types of demand that cannot be accepted and the total number of types of demands. Energy efficiency is the ratio of the total traffic demand successfully served in the network to the total energy consumption of the network (Vizcaíno et al., 2012).

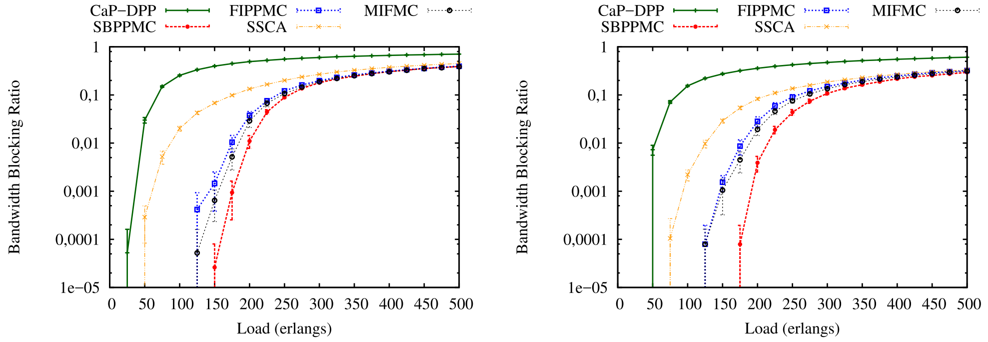
The following sections show the curve obtained with the FIPPMC, SBPPMC and MIFMC algorithms for the four topologies. Moreover, results are compared to those derived by the CaP-DPP (Tan et al., 2016) and SSCA (Tode and Hirota, 2014) algorithms. The CaP-DPP uses a crosstalk-aware provisioning strategy with dedicated path protection whereas SSCA algorithm uses a K-shortest path algorithm for computing routes in the simulation, we used $K = 3$. In the SSCA algorithm the primary path is treated independently, i.e., the routing problem is dealt independently and the SCA problem considering the distance between source and destination. This approach employs multiple pre-computed routes, with backup path created in the same way as the primary path but using a 1:N scheme for the backup path.

5.1. Bandwidth blocking ratio

Fig. 4(a)–(d) show the bandwidth blocking ratio (BBR) as a function of the load for the Pan-European, USA, NSF, Cesnet and Italy topologies, respectively.



(a) Pan-European (b) USA



(c) NSF (d) Cesnet

Fig. 4. Bandwidth blocking ratio.

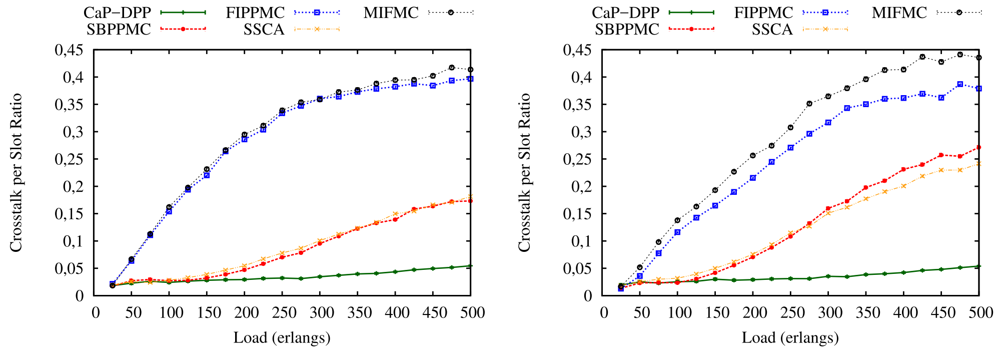
For the Pan-European topology, while SBPPMC, FIPPMC and MIFMC start blocking requests only under loads of 75 erlangs, whereas with the CaP-DPP and SSCA algorithms under loads of 50 erlangs. The BBR values produced by the MIFMC algorithm is always lower than that of the others, which evinces the benefits of considering the minimum interference criteria to create the p-cycles when choosing the backup route for topology with high connectivity. The FIPPMC and MIFMC algorithms lead to similar BBR behavior. Due to the high node connectivity in the Pan-European topology none of the algorithm using p-cycle blocks request until 75 erlangs. The CaP-DPP algorithm produced the highest BBR, because it does not use shared paths to provide protection. The difference between the BBR produced by the FIPPMC and MIFMC algorithms is almost three orders of magnitude lower than that produced by the SSCA, one order of magnitude lower than that produced by the SBPPMC, and almost four orders of magnitude lower than with that produced by the CaP-DPP algorithm. Under high loads of 300 erlangs, the use of all the evaluated algorithms led similar high BBR behavior.

For the USA topology, CaP-DPP and SSCA algorithms started blocking requests under loads of 50 erlangs, whereas the FIPPMC and MIFMC algorithms start blocking requests under loads of 125 erlangs and the SBPPMC algorithm starts blocking requests under loads of 150 erlangs. The MIFMC algorithm produced the lowest BBR values followed by the SBPPMC algorithm were better able to take advantage of the high node connectivity in the USA topology. Under loads of 150 erlangs, the MIFMC and SBPPMC algorithms led to similar BBR values, with the employment of minimal interference criterion compensating for the fact that the use of p-cycles consumes more resources than do shared backup protective schemes. The BBR values produced by these two algorithms are more than three order of magnitude lower than those given by the CaP-DPP algorithm, more that two orders of magnitude lower than those produced by with the SSCA and more that one order of magnitude lower than those provide by the FIPPMC algorithm. For loads up to 200 erlangs the MIFMC algorithm combines the advantages of sharing p-cycle and minimum interference thus leading to less blocking than the other algorithms evaluated.

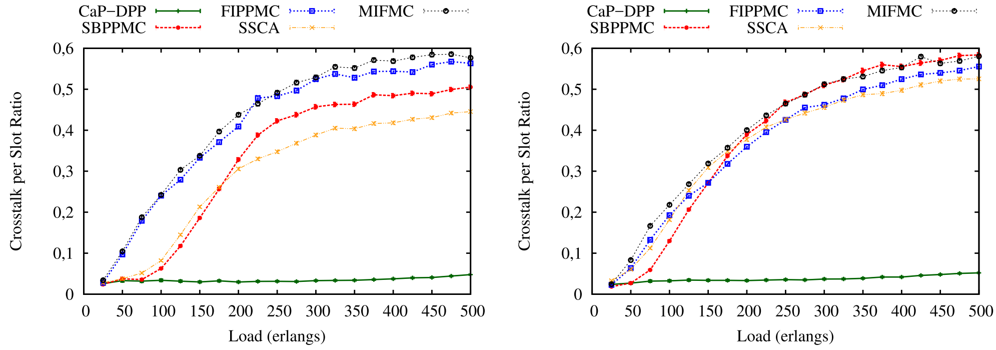
For the NSF topology with much less connectivity, while CaP-DPP and SSCA start blocking requests under loads of 25 and 50 erlangs, respectively, the FIPPMC and MIFMC only start blocking requests under loads of 125 erlangs and SBPPMC only under loads of 150 erlangs. The BBR values produced by SBPPMC algorithm are the lowest ones as the result of the creation of shared backup paths by employing multigraphs. Under 150 erlangs, the BBR produced by this algorithm is almost one order of magnitude lower that those produced by the FIPPMC and MIFMC algorithms, because the low node connectivity in the NSF topology allows a lower number of FIPP p-cycles to be created. Such connectivity reduces the difference in BBR produced by the FIPP and MIFMC, and leaves the use of minimum interference criteria less effective. Under 125 erlangs, the BBR given by the MIFMC algorithm is almost one order of magnitude lower than that produced by the FIPPMC algorithm, as a consequence of MIFMC using the minimum interference approach. The CaP-DPP algorithm which does not share backup paths, produces the highest BBR values, regardless of the topology as a consequence of not sharing backup path.

For the Cesnet topology, both CaP-DPP and SSCA start blocking requests under low loads of 50 and 75 erlangs, respectively, whereas the FIPPMC and MIFMC start blocking only under loads of 125 erlangs and the SBPPMC algorithm starts only under loads of 175 erlangs. The BBR values yielded by SBPPMC algorithm are the lowest ones. The low node connectivities prevents the creation of several FIPP p-cycle. Under loads of 175 erlangs, the SBPPMC algorithm producing values almost two order of magnitude lower than those produced by the FIPPMC and MIFMC algorithms, and almost three orders of magnitude lower than those produced by SSCA algorithm. Again the non sharing of backup paths leads the CaP-DPP algorithm produce the highest BBR values.

These results indicate that the fine grain allocation of the spectrum facilitated by the adoption of a multigraph representation of the spectrum leads to efficient allocation and, consequently, to a reduction in blocking. Consequently, the FIPPMC, MIFMC and SBPPMC algorithms produce acceptable blocking for SDM with multicore fibers, in despite the bandwidth reserved for pre-provisioning of backup paths. More-



(a) Pan-European (b) USA



(c) NSF (d) Cesnet

Fig. 5. Crosstalk per slot ratio.

over, p-cycle based algorithms also benefit from high node connectivity due to the possibility of allocating several paths.

5.2. *Crosstalk per slot ratio*

The employment of multiple cores generates intercore crosstalk. Fig. 5(a)–(d) shows the “Crosstalk per Slot” (CpS) as a function of the load for the four topologies.

For the Pan-European topology, the FIPPMC and MIFMC algorithms produce the highest CpS values, because these algorithms accept more connections than do the other ones. These connections generates greater crosstalk interference. The CpS generated by the FIPPMC and MIFMC algorithm increases quickly with the load increase since the greater the number of hops used leads to greater resource utilization and consequently more CpS. Although the SSCA algorithm produces larger BBR than does the SBPPMC algorithm, the allocation made by these two algorithms produce similar CpS. This happens because the employment of multigraphs leads to the use of short paths demanding fewer resources and generating less CPS.

As in Pan-European topology the FIPPMC and MIFMC algorithms produce the highest CpS than do the other three algorithms with the MIFMC producing the highest level. This CpS is a consequence of the high network utilization, generated by the higher number of requests accepted. The CpS generated by the SBPPMC is less than generated by the FIPPMC and MIFMC although the SBPPMC algorithm produces lower BBR values than do the FIPPMC and MIFMC algorithm since the use of p-cycle consumes more network resources. Although the SBPPMC and SSCA algorithms generate similar amount of CpS, the SBPPMC is preferably since it produces smaller BBR values as well.

Besides the SBPPMC algorithm producing low blocking and high utilization for the NSF topology, it also produce low CpS. The SBPPMC algorithm produces the lowest crosstalk when compared to the FIPPMC and MIFMC algorithms as a consequence of connections being more uniformly distributed. The SSCA algorithms have a CpS closer to that of FIPPMC, MIFMC and SBPPMC although it blocks more connections.

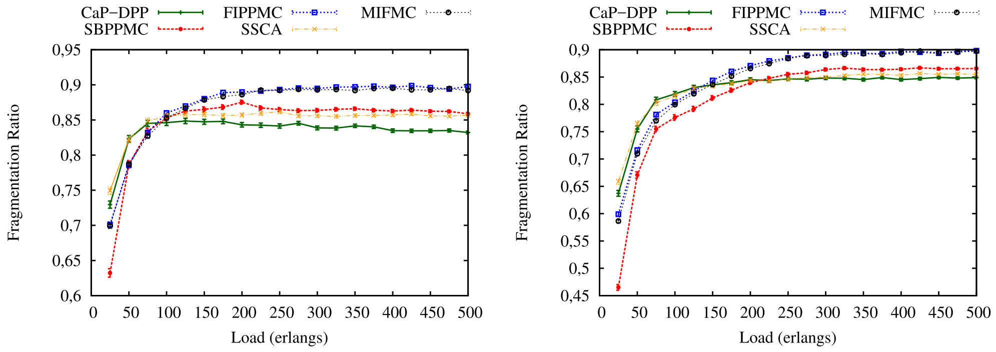
For Cesnet topology, besides the SBPPMC, FIPPMC and MIFMC algorithms producing low blocking and high utilization, while producing similar crosstalk per slot to that generated by the SSCA algorithm. The CaP-DPP algorithm produces the highest BBR values due to the use of the shortest path, generating less CpS.

Results show that the smaller the BBR values are, the greater is the utilization and consequently the greater the crosstalk ratio. The algorithms that use p-cycles produce lots of crosstalk per slot, because the creation of p-cycles uses a more of the resources of the network, and the slots used have more adjacent slots. Although the backup paths are not active the CpS must be evaluated since their possible use will still yield crosstalk which must be at acceptable level of CpS. Another important feature is the lower the connectivity of the topology, the less difference between closer the results between them.

5.3. *Fragmentation ratio*

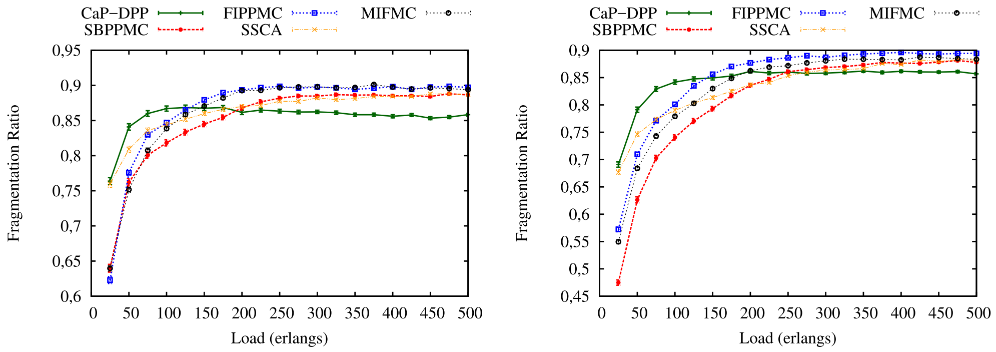
Fig. 6(a)–(d) depict the Fragmentation Ratio as function of the load for Pan-European, USA, NSF and Cesnet, topologies, respectively.

For the Pan-European topology, the CaP-DPP algorithm produces the lowest fragmentation ratio a consequence of the smaller number of requests accepted and the shortest paths used. The MIFMC algorithm produces a fragmentation ratio 2% lower than that given by the FIPPMC algorithm, as a consequence of the use of p-cycle straddling to the backup path, which uses a greater number of links. Straddling p-cycles tends to share a higher number of connections established as a consequence, the links along these p-cycles tend to be deallocated less often. The FIPPMC and MIFMC algorithms produce fragmentation ratio almost 10% higher than that given by the SBPPMC algorithm, since more requests are accepted by FIPPMC and MIFMC algorithms which the de-allocation of connection generates more fragmentation.



(a) Pan-European

(b) USA



(c) NSF

(d) Cesnet

Fig. 6. Fragmentation ratio.

For the USA topology, the CaP-DPP algorithm produces fragmentation ratio 2% lower than that produced by the SSCA algorithm, as a consequence of the smaller number of requests accepted and shorter paths allocated. The FIPPMC algorithm produces fragmentation ratio 4% higher than that given by MIFMC algorithm, as a consequence of straddling p-cycles having a greater number of shared links which decreases the number of deallocation of this links. The FIPPMC algorithm produces fragmentation ratio 8% higher than that given by the SBPPMC algorithm, despite the higher number of requested accepted by the SBPPMC algorithm.

For the NSF topology, until loads of 200 erlangs SSCA algorithm produces lower fragmentation ratio than does the CaP-DPP algorithm, as a consequence of shared backup paths being kept active for longer time and producing less disconnection. Under highs loads the BBR produced by the CaP-DPP and SSCA algorithms are similar, however the CaP-DPP algorithm produces fragmentation ratio 5% lower than that given by SSCA as a consequence of the smaller number of requests accepted by the CaP-DPP algorithm. The FIPPMC algorithm produces fragmentation ratio 1% higher than that produced by the MIFMC in despite of the FIPPMC algorithm producing higher BBR values. This happens due to the larger size of the p-cycles generated by the MIFMC, shared by higher number of primary paths which leads to a lower number of deallocation of these shared links. The SBPPMC algorithm produces fragmentation ratio 7% lower than that given by FIPPMC, since SBPPMC produces smaller BBR values. This is a consequence of algorithms that use p-cycles allocating a higher number of links, so when these p-cycles are de-established they produce a larger number of deallocation of links, generating more fragmentation.

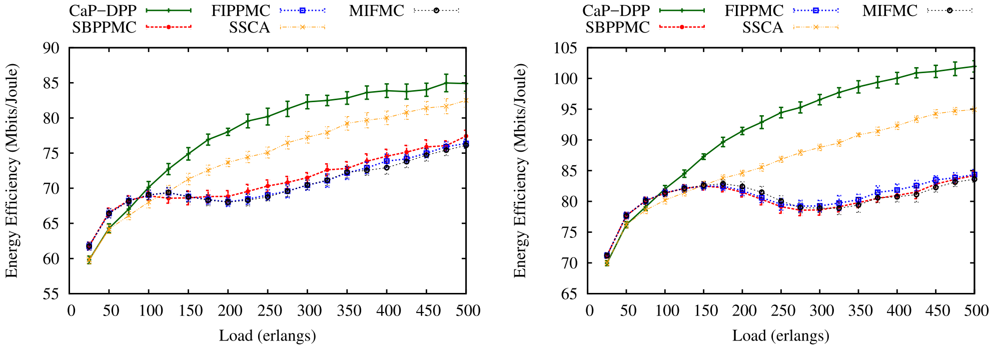
For the Cesnet topology, until loads of 250 erlangs, the SSCA algorithm produces lower fragmentation ratio than does the CaP-DPP algorithm, due to the high BBR produced by CaP-DPP algorithm. Under high loads the BBR produced by the CaP-DPP and SSCA algorithms are close, however the CaP-DPP algorithm produces fragmentation ratio 2% lower than that given by the SSCA algorithm as a consequence of the smaller number of requests accepted by the CaP-DPP algorithm. Regardless of the load, the SBPPMC produces fragmentation ratio lower than that produced by the FIPPMC and MIFMC algorithms. Under high loads the SSCA produces lower fragmentation ratio than the SBPPMC algorithm.

For all topologies, the fragmentation ratio produce by all algorithms are similar and influenced by the number of request blocked. The higher the load the higher is the fragmentation ratio as a consequence of the higher number of the allocation of links. Algorithms that use p-cycle tend to lead to a greater fragmentation, as a consequence of the larger number of links used.

5.4. *Energy efficiency*

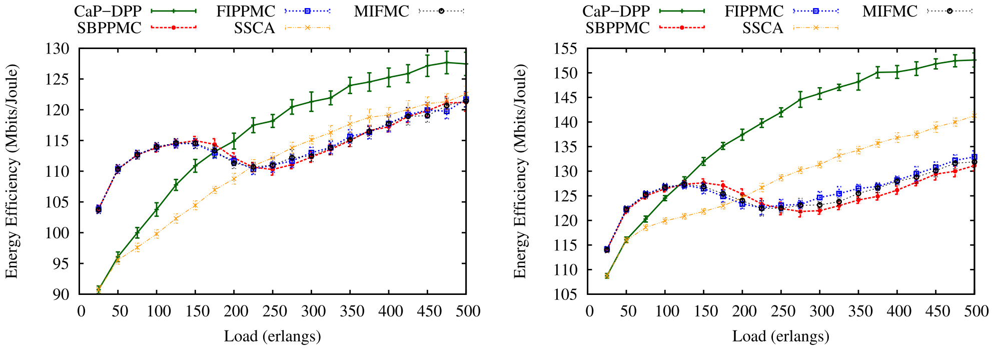
Fig. 7(a)–(d) illustrates the energy efficiency of the algorithms for the Pan-European, USA, NSF and Cesnet topologies, respectively. For the Pan-European topology, under high loads the CaP-DPP produces the greater energy efficiency, while the FIPPMC and MIFMC produce the least. There is not much difference between the energy efficiency of the SBPPMC and that of algorithms that use p-cycles. The differences arise only under heavy load, since FIPPMC and MIFMC produces significantly lower blocking ratios. The SSCA algorithm is especially lower in energy efficiency, despite the high blocking values.

For the USA topology, up to loads of 150 erlangs, there is not much difference between the energy efficiency of CaP-DPP and from other algorithms. The difference arises only under heavy load. Under high loads, however, the CaP-DPP is more efficient in energy use than is the SSCA algorithm, since CaP-DPP produces more blocking. Under loads greater than 175 erlangs the energy efficiency for the SSCA algorithm is greater than that of the FIPPMC, SBPPMC and MIFMC algorithms due to he higher blocking it these loads. There is not much difference between the energy efficiency of the SBPPMC algorithm and that using p-cycle.



(a) Pan-European

(b) USA



(c) NSF

(d) Cesnet

Fig. 7. Energy efficiency.

For the NSF topology, until loads of 175 erlangs, the SBPPMC, FIPPMC and MIFMC produces higher energy efficiency than do SSCA and CaP-DPP algorithms, despite SBPPMC, FIPPMC and MIFMC producing significantly lower blocking ratios. As for the USA topology under high loads the CaP-DPP produces high energy efficiency than does the SSCA algorithm, since CaP-DPP blocks more requests. Under high loads, the SSCA algorithm produces energy efficiency similar to those of SBPPMC, FIPPMC and MIFMC algorithms. Under loads lower than 150 erlangs, the SBPPMC, FIPPMC and MIFMC algorithms have similar energy consumption. Under loads greater than 225 erlangs although the SSCA algorithm produces a higher BBR values than do the FIPPMC, SBPPMC and MIFMC algorithms, but they still have similar energy efficiency.

For the Cesnet topology, under high loads, the FIPPMC produces higher energy efficiency than does the MIFMC algorithm, and MIFMC produces higher energy efficiency than does the SBPPMC algorithm since the higher the BBR the lower is the energy efficiency. Until loads of 100 erlangs there is not much difference between the energy efficiency of CaP-DPP and SSCA, despite CaP-DPP producing significantly higher blocking ratios under these loads. Until loads of 200 erlangs the SBPPMC, FIPPMC and MIFMC produces higher energy efficiency than do the SSCA and CaP-DPP algorithms, despite SBPPMC, FIPPMC and MIFMC producing significantly lower blocking ratios under these loads.

In general, the algorithms that blocks a higher number of requests tends to produce higher energy efficiency since these algorithms do not employ long paths. However, the use of multigraph to represent the spectrum changes these results, since this representation allows allocation of a higher number of short paths.

5.5. Summary of results

In summary, for all topologies, the BBR values produced by CaP-DPP are always the highest, due to the use of non-shared protection techniques. This is also related to the way the paths to be allocated are searched, as this can lead to great fragmentation. However, high fragmentation and high blocking generate a large number of available slots, which leads to low crosstalk.

The BBR values produced by SSCA are always lower than those produced by the CaP-DPP algorithm, due to the employment of shared protection techniques, but they are always higher than those produced by the FIPPMC, MIFMC and SBPPMC algorithms, since multigraphs not used to seek primary and backup paths. The use of multigraphs allows the FIPPMC, MIFMC and SBPPMC algorithms to find better paths in relation to network availability and avoid a certain amount of fragmentation. Although the SSCA algorithm produces higher BBR than does the SBPPMC algorithm, the generated CpS values are similar to the one produced by the SBPPMC algorithm. This happens because the multigraph and the algorithm that chooses the route in the SBPPMC distribute more the connections along the network, leading to lower fragmentation ratio.

The performance of the MIFMC and FIPPMC algorithms are affected by the low connectivities of the network nodes, and, they consequently generate higher BBR than does the SBPPMC algorithm in topologies such as CESNET and NSF. On the other hand, in topologies with greater connectivity such as Pan-European and USA, the FIPPMC and MIFMC algorithms can create more p-cycles, which evinces the advantage of the use of p-cycles for protection.

The FIPPMC algorithm uses more resources in creating backup paths than does the SBPPMC algorithm, which makes more slots unavailability, and consequently leads to more crosstalk, more fragmentation, and lower energy efficiency. On the other hand, the greater the number of hops in the p-cycle and the pre-configuration feature in the FIPPMC algorithm leads to greater sharing, which is especially beneficial in topologies with high node connectivity. The FIPPMC algorithm also takes advantage of the high network node connectivity. However, in order to further explore this feature, the MIFMC algorithm takes advantage of minimum interference to reduce congestion network links and, consequently, reduce the blocking of request, although the requests use more network resources and increases the CpS, thus decreasing the energy efficiency.

6. Conclusion

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 fewer algorithms to support the establishment of lightpaths in spacial division multiplexing elastic optical networks protected by shared path protecting. The proposed algorithms use techniques such as FIPP p-cycle, minimal interference and shared backup paths to provide 100% protection against single failures. Moreover, the node connectivity has been found to produce great impact on protection of networks. Extension of the proposed SBPPMC and FIPPMC algorithms to include adaptive modulation have been developed (Oliveira and da Fonseca, 2017c; Oliveira and da Fonseca, 2018).

As future work, we aim at evaluating the introduction of spectrum overlap in backup paths. Spectrum overlap allows two backup lightpaths to use the same cores, links and spectrum, if the working paths of the two connections are physically disjoint. The use of spectrum overlap decreases the utilization of resources for protection and, consequently, increases the gain in spectrum utilization.

In addition, we intend to develop multipath algorithms for protection of EON-SDM. The use of multipath routing offers the advantage of using small contiguous bands in different paths to satisfy requests for lightpath establishment, which can potentially increase the number of accepted requests.

Acknowledgments

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