Algorithm for Protection of Space Division Multiplexing Elastic Optical Networks

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Abstract

In recent years, elastic optical networks have emerged as a solution for dealing with the diversity of the bandwidth demands of network applications. The use of only two multiplexing dimensions has limited the network capacity. To ameliorate this problem, a third dimension has been added in space-division multiplexing (SDM). As transmission rates increase so does the need for protection against network failures. Among the protection schemes, those protecting paths are of great interest due to their end-to-end solutions. This paper introduces a novel algorithm based on p-cycle to provide failure-independent path protection in elastic optical networks with SDM.

1 Introduction

The increasing demand of bandwidth and the rapid approaching capacity limitation of single-core optical fibers has led to the exploitation of the only unused dimension to increase the network capacity. Space division multiplexing (SDM) introduces the concept of using multiple fibers in parallel, providing an n-fold increase in the usable spectral resources and the introduction of a new "space" dimension [2]. Space division multiplexing can be realized using multimode fiber (MMF), multicore Fiber (MCF) and 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. Moreover, new techniques need to be developed to realize SDM.

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 [4]. 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.

Although algorithms for spectrum allocation have been proposed [5, 6, 4, 7, 8], no study related to protection in SDM elastic optical networks has been proposed so far. Survivability is of paramount importance in optical transport networks that carry huge amount of traffic. Increasing the number of cores increases the capacity of the network, resulting in greater need for protection.

Most of the protection techniques reserve but do not pre-configured backup resources, which may result in long signaling procedure during restoration [9]. p-Cycle is a protection technique with

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pre-configure backup resources. The spare capacity is used to provide protection to the working paths. p-Cycle can protect all the on-cycle spans as well as straddling spans. p-Cycle combines the advantage of mesh networks with the restoration speed of ring networks [10]. A special case of p-cycle for path protection is the so called Failure-Independent Path Protecting p-cycles (FIPP) [11]. FIPP p-cycles furnish protection to end-to-end working (primary) path with end nodes on the p-cycle. FIPP is an extension of the p-cycle concept in which failure is not limited to a link or path segment immediately adjacent to the end nodes. FIPP p-cycle has been studied for protecting EONs. However, no study has shown FIPP p-cycles for protection of elastic optical network with SDM (SDM-EONs) [11, 12, 13, 14, 9, 15, 16].

In this paper, we propose an algorithm called FIPPMC for providing FIPP p-cycle protection in SDM-EONs and we evaluate the perfomance of the algorithm as a function of the number of cores in elastic optical networks with spacial division multiplexing. 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 for playing a key role in SDM-EON protection.

This paper is organized as follows. Section 2 reviews related work. Section 3 introduces the proposed algorithm. Section 4 evaluates the performance of the proposed algorithm and Section 5 concludes the paper.

2 Related Work

The emergence of elastic optical networks has motivated several investigations, mainly on RSA algorithms but only recently RSCA solutions have been proposed. The authors in [5] divided the RSCA problem into the routing and SCA problems, and introduced a K-shortest path based pre-computation method as the routing solution. They proposed SCA methods with crosstalk awareness. In [6], it is investigated the spectrum fragmentation issue, which undermines the bandwidth efficiency in elastic optical networks. Fujii *et al.*[4] proposed an "on-demand" spectrum and core allocation method to reduce both crosstalk and fragmentation in elastic optical networks with MCFs. Proietti *et al.* [7] extends 2D-EON to include elasticity in all three domains: time, frequency, and space. They investigated algorithms for routing, spectrum, spatial mode, and modulation format assignment. In [3], a network with three-layer (IP/MPLS-over-OTN-over-DWDM) is considered. An optimization modeling framework incorporating modularization of its capacity for protection in any layer is used. The authors in [8] investigated the routing, spectrum and core allocation (RSCA) problem for flexgrid optical networks. They formulated the RSCA network planning problem using integer linear programming (ILP) formulation as well a heuristic. In [17], it is introduced a Routing, Core and Spectrum Assignment (RCSA) algorithm based on the Connected Component Labelling (CCL) algorithm. In [18], it is proposed an architecture for optical cross-connect (OXC) called architecture on demand (AOD) and it is shown that AOD provides much higher flexibility than do other architectures. The optimization problem for a cost-efficient architecture for SDM networks with AoD OXCs is formalized as an integer linear programming (ILP) problem. The implementation of FIPP-p-cycles in EONs was studied in [12, 13, 19, 14]. To the best of our knowledge, no other work has considered protection in SDM elastic optical networks.

3 The Algorithm

Similar to the routing and spectrum assignment (RSA) problem in elastic optical networks, solutions to the RSCA problem in elastic optical networks are needed to efficiently accommodate diverse traffic demands. In an RSCA formulation, routing can switch cores and links. Moreover, the problem formulation needs to consider the spectrum continuity constraint, which imposes that the allocation of the same spectrum in each fiber along the route of a lightpath, as well as the spectrum contiguity constraint, which imposes that the slots must be contiguously allocated in the spectrum.

The proposed algorithm models the spectrum availability in the network as labeled multigraph (Figure 1). A multigraph is a graph which can have multiple edges (also called "parallel edges"), i.e., edges that have the same end vertice. In this auxiliary graph, vertices represent OXCs and edges represent sets of the same slots in different cores in the link connecting the OXCs. All the vertices are connected by N edges which is the number of slots in the spectrum of each network link, and each edge represents one slot regardless of the core. Labels on an edge represent the availability of a slots. An ∞ value means that all slots are already allocated whereas the value 1 means that at least one slot is available for allocation. These values were defined to facilitate the employment of traditional shortest path algorithms.

3.1 Notation

The following notation will be used in the paper:

s: source node;

d: destination node;

b: bandwidth demand in slots, $b = 1 \dots N$;

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

N: number of slots set between two nodes;

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

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

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

$e'_{u,v,n,j}$: where j is a channel chosen to be used.

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

$\widetilde{G}_{n,b} = (\widetilde{V}, \widetilde{E}, \widetilde{W})$: 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 $n^{th} edge$;

$\widetilde{V} = V$: 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 $\widetilde{e}_{\widetilde{u},\widetilde{v}}$;

$\widetilde{W}_n = \{\widetilde{w}_n(\widetilde{e}_{\widetilde{u},\widetilde{v}})\}$: set of edge weights;

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

$W(\widetilde{P}_n)$: $\sum_{\widetilde{e}_{\widetilde{u},\widetilde{v}} \in \{\widetilde{P}_n\}} \widetilde{e}_{\widetilde{u},\widetilde{v}}$: the weight of the path $\widetilde{P}_n$ (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;

$\widetilde{t}_{u,v,b}$: p-cycle containing vertices u and v and edges corresponding to the mapping of b edges of the multigraph G;

$\widetilde{T}_{u,v,b} = \widetilde{t}_{u,v,b}$: set of all p-cycles containing vertices u and v and edges corresponding to the mapping of b edges of the multigraph G;

$\widetilde{T}$: set of all established p-cycles and active;

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

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

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

3.2 FIPPMC Algorithm

The algorithm introduced in this subsection, called FIPPMC (Failure-Independent Path Protecting for MultiCore network) decides on the establishment of lightpaths in an FIPP p-cycle protected network. 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.

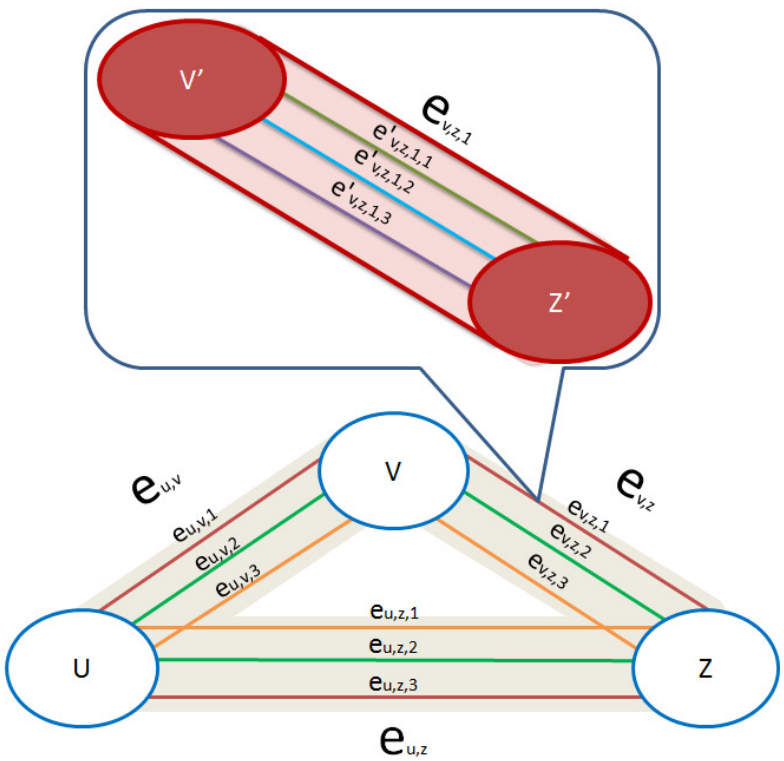


Figure 1: Multigraph

An FIPP p-cycle protects disjoint primary paths. Requests to lightpath establishment arrive dynamically and for each request an existing p-cycle is searched to protect the potential lightpath. In case no existing p-cycle can protect the potential lightpath then a path is searched to create a new p-cycle for the request. If no path can protect the lightpath then it is not established. The

FIPPMC algorithm assures a protection path to each established lightpath and the protection is guaranteed against single failures.

Algorithm 1 FIPPMC

1: $\forall n = 1...N-b$
2: $\quad (W(P_n), P_n) = ShortestPath(\widetilde{G}_{n,b}, r(s,d,b))$
3: $W_{P_{s,d}} = W(P_n) |\ \forall i\ W(P_n) \leq W(P_i)$
4: **if** $W_{P_{s,d}} = \infty$ **then**
5: $\quad$ *block* $r(s,d,b)$
6: **else**
7: $\quad$ **if** $T_n \neq \emptyset \quad \forall\ T_n \in \widetilde{T}$ **then**
8: $\quad\quad$ establish $r(s,d,b)$ as P_n and T_n
9: $\quad\quad W(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \widetilde{P}_i \quad n = n...i{+}b-1$
10: $\quad$ **else**
11: $\quad\quad (W(T_n), T_n) = ShortestCycle\ (\widetilde{G}_{n,b}, r(s,d,b))$
12: $\quad\quad W_{T_{s,d}} = W(T_n) |\ \forall i\ W(T_n) \leq W(T_i)$
13: $\quad\quad$ **if** $W_{T_{s,d}} = \infty$ **then**
14: $\quad\quad\quad$ block $r(s,d,b)$
15: $\quad\quad$ **else**
16: $\quad\quad\quad$ establish $r(s,d,b)$ as $\widetilde{P}_n$ and $\widetilde{T}_n$
17: $\quad\quad\quad W(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \widetilde{P}_i \quad n = n...i{+}b-1$
18: $\quad\quad\quad W(e'_{u,v,i}) = \infty \quad \forall\{u,v\} \in \widetilde{T}_i \quad n = n...i{+}b-1$
19: $\quad\quad$ **end if**
20: $\quad$ **end if**
21: **end if**

In this algorithm, Line 1 establishes all the set of edges that will be mapped onto $\widetilde{G}_{n,b}$ edges. Line 2 solves a shortest path algorithm for the graph $\widetilde{G}_{n,b}$ and provides the path and its weight. If the weight of the shortest path is ∞, it was not possible to find a path under the contiguity constraint for the demand b with allocation starting with the n^{th} slot. Line 3 selects the path among the $N-b+1$ 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. Therefore, the request has to be blocked (Line 5). If there is no path available (Line 4) then the request is blocked (Line 5). Otherwise, a p-cycle to protect the lightpath to be established is searched (Line 7). In case, 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 were allocated to the newly established lightpath. Otherwise, a p-cycle to protect the lightpath to be established needs to be created (Lines 11). In case no p-cycle can be created to protect the lightpath then the request is blocked (Line 13 and 14), otherwise the lightpath as well as the p-cycle (Lines 16) are established to satisfy the request. The corresponding edges in the multigraph G have their weight changed to ∞ (Line 17 and 18), meaning that the slots were allocated to the newly established lightpath.

4 Performance Evaluation

To assess the performance of FIPPMC algorithm in multi-core networks cores, simulation experiments were employed increasing the number of cores in the range [1, 3, 5, 7] (Figure 2). The

FlexGridSim [20] simulator was employed. In each simulation, 100,000 requests were generated and simulations for the algorithm used the same set of seeds. Confidence intervals were derived using the independent replication method with 95% confidence level. The topology used in the simulations were the NSF (Figure 3b), and the USA (Figure 3a) topologies. The NSF topology has 16 nodes and 25 links whereas the USA topology has 24 nodes and 43 links (Figure 3).

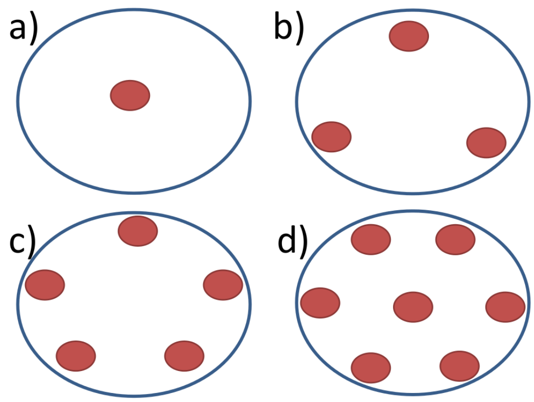
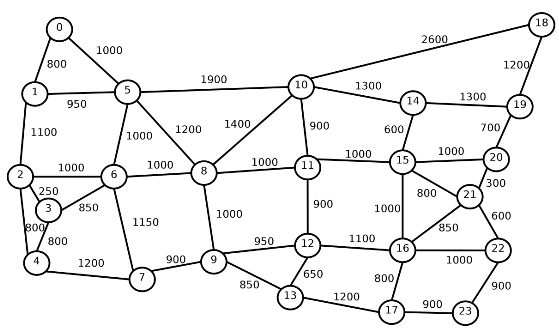
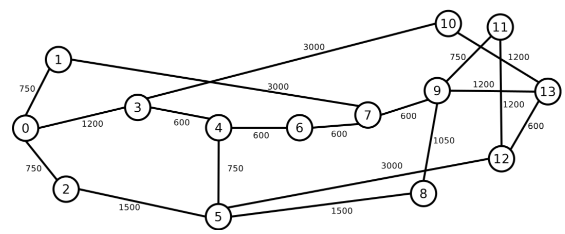


Figure 2: Cores distribution



(a) USA Topology



(b) NSF Topology

Figure 3: Topologies

The mean arrival rate and the mean holding time were adjusted to simulate the desired load in erlangs. The spectrum was divided in 240 slots of 12,5 GHz each. In the figures, the curves labeled ”FIPPMC1” show the results for networks using the algorithm FIPPMC and single-core fiber (SCF), while the curves labeled FIPPMC3, FIPPMC5 and FIPPMC7 display, respectively, results for networks using the algorithm FIPPMC and three-core fiber (3MCF), five-core fiber (5MCF) and seven-core fiber (7MCF). The load was increased in units of 25 erlangs.

Figure 4 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. The FIPPMC algorithm impacts differently blocking in networks with different number of cores. As expected the higher the number of cores, the lower is the BBR value for a given load. For a single core network, blocking occurs under loads as low as 25 erlangs and BBR values of 0.01 are produced for loads higher than 50 erlangs. However, such blocking values do not happen when the FIPPMC algorithm is used in multi core fibers. For 3MCF, blocking occurs under loads higher than 70 erlangs and BBR values reach 0.01 under loads of 100 erlangs. For fibers with 5 and 7 cores, blocking occurs only under 130 erlangs and 230 erlangs, and reaches a value of 0.01 under loads of 190 erlangs and 330 erlangs, respectively. These results show that the FIPPMC algorithm

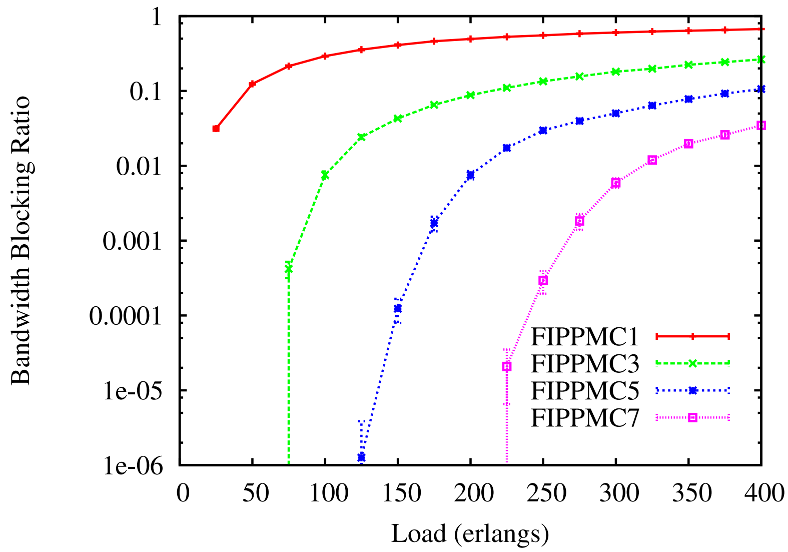


Figure 4: Bandwidth blocking ratio for USA topology

produces acceptable blocking for SDM with multicore fibers in despite of the bandwidth reservation for pre-provisioning of backup paths.

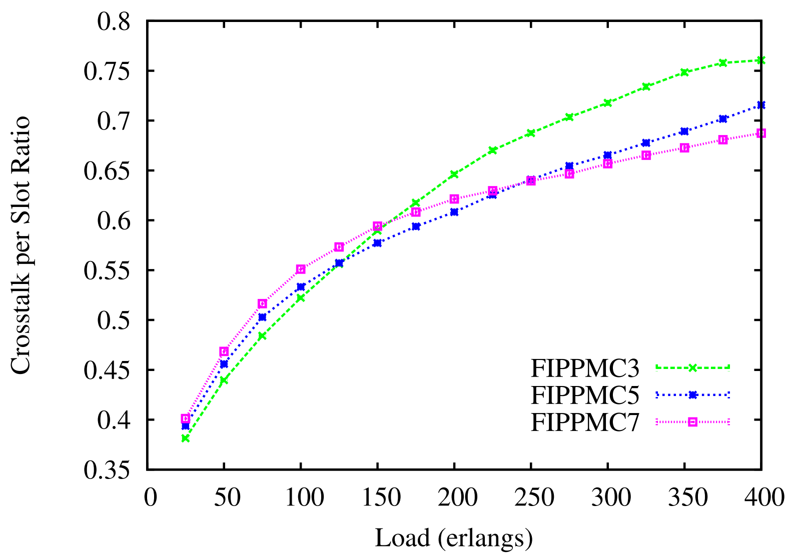


Figure 5: Crosstalk per slot ratio for USA topology

The use of several cores generates inter-core crosstalk. Figure 5 shows the “Crosstalk per Slot” (CpS) as a function of the load for USA topology. The crosstalk value for each spectrum slot is defined as the ratio of the actual crosstalk index to the maximum value of the crosstalk index. The crosstalk ratio is defined by the average value among all spectrum slots [4]. The generated CpS for the FIPPMC algorithm starts at a 0.37 value and increases quickly with the load increase since a higher number of cores leads to lower blocking and less usage of the full network capacity. In these load scenarios, less crosstalk is produced since connection are more uniformly distributed. The generated CpS for the FIPPMC algorithm in 7MCF remains between 0.6 and 0.66 under heavy loads.

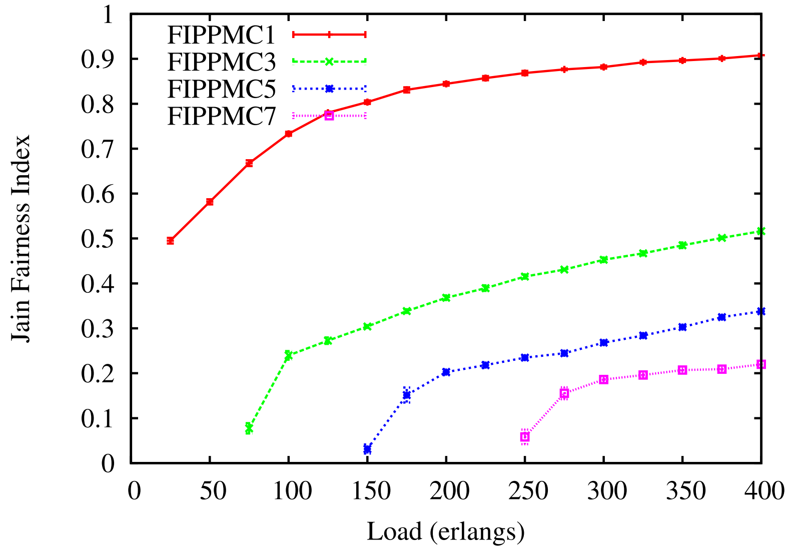


Figure 6: Jain fairness index for USA topology

Figure 6 displays the Jain Fairness Index (JFI) of the BBR for different source destination pairs and for the USA topology. The FIPPMC algorithm applied in SFC has high Jain index values due to high blocking produced which affects uniformly all source destination pairs. The FIPPMC algorithm produces low Jain Index of fairness for MCF networks since several source destination pairs do not suffer blocking, especially under low loads.

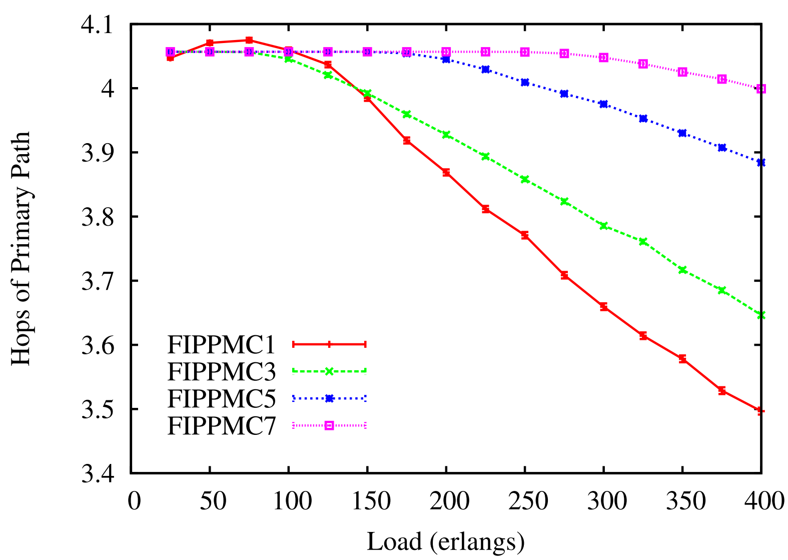


Figure 7: Average number of hops allocated per primary path for USA topology

Figure 7 shows the average number of hops of primary paths established for the USA topology. The higher the load, the smaller is the average number of hops allocated per primary path. This happens because under high loads, only short paths are possible to be established given that the spectrum is already allocated. The capacity of path allocation is reduced significantly for SCF and 3MCF as blocking increases under high loads. However, 7MCF maintains the capacity of establishing paths with different length as can be seen by the almost constant average path length.

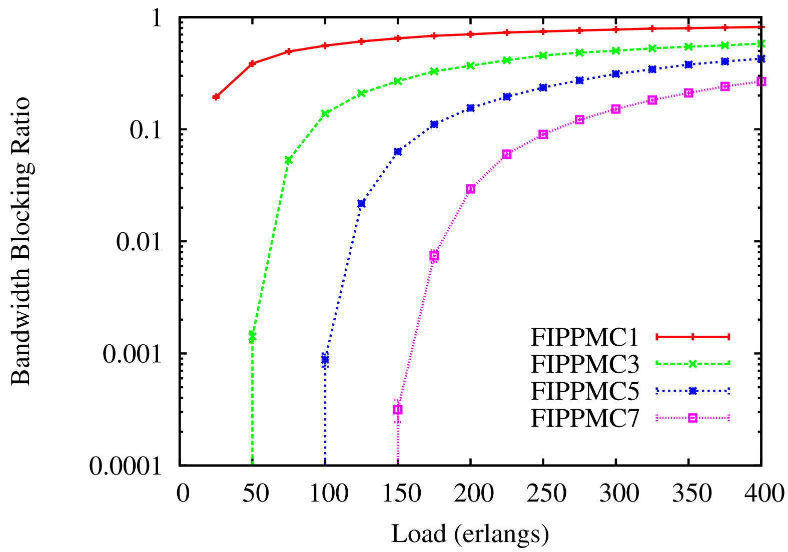


Figure 8: Bandwidth blocking ratio for NSF topology

Figure 8 shows the bandwidth blocking ratio (BBR) as a function of the load for the NSF topology. The low node degree in this topology leads to the creation of bottlenecks and a much faster increase in blocking when compared to the blocking for the USA topology. For SCF, 3MCF, 5MCF and 7MCF blocking occurs under loads 25, 50, 100 and 150, respectively. For the NSF topology, the FIPPMC algorithm is recommended to be used under loads lower than 150 erlangs. The BBR achieves unacceptable values after 150 erlangs which is already a heavy load.

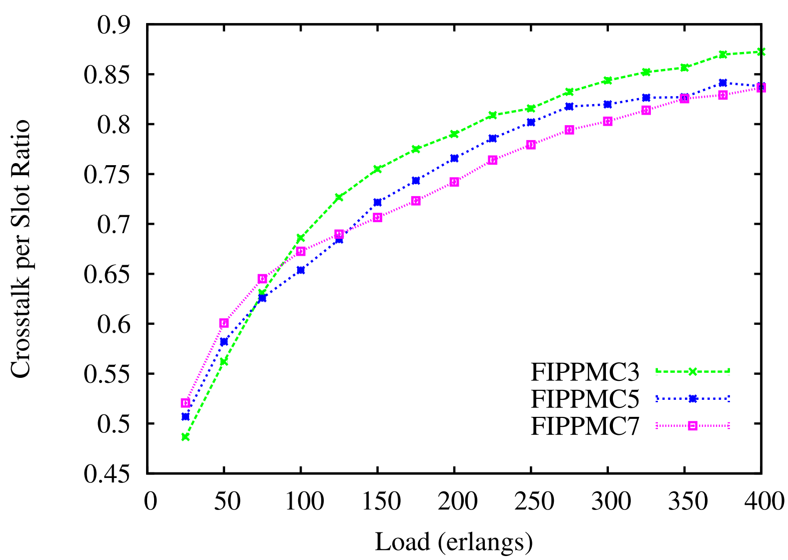


Figure 9: Crosstalk per slot ratio for NSF topology

Figure 9 shows the "Crosstalk per Slot" (CpS) as a function of the load for the NSF topology. The algorithm FIPPMC in SCF does not produce CpS because there is no adjacent core. The effect of the high utilization of the network capacity clearly affects the CpS when compared to that of the USA topology. The CpS values are much higher for the NSF topology and there is not much difference in CpS as a function of the number of cores. In protected networks, the higher the CpS, the higher is the blocking probability. Moreover, in 3MCF, 5MCF and 7MCF, CpS starts between 0.47 and 0.52; such values are due to the high utilization of the network capacity. It can be seen that the average CpS is correlated with the bandwidth blocking ratio.

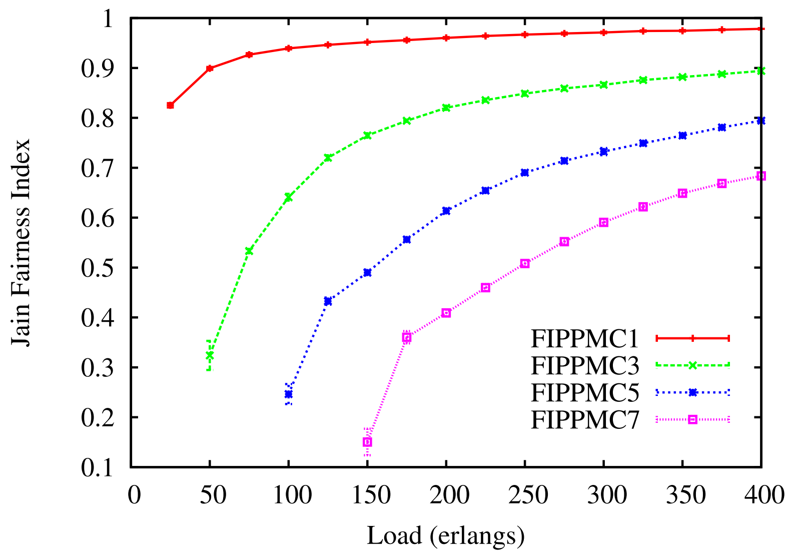


Figure 10: Jain fairness index for NSF topology

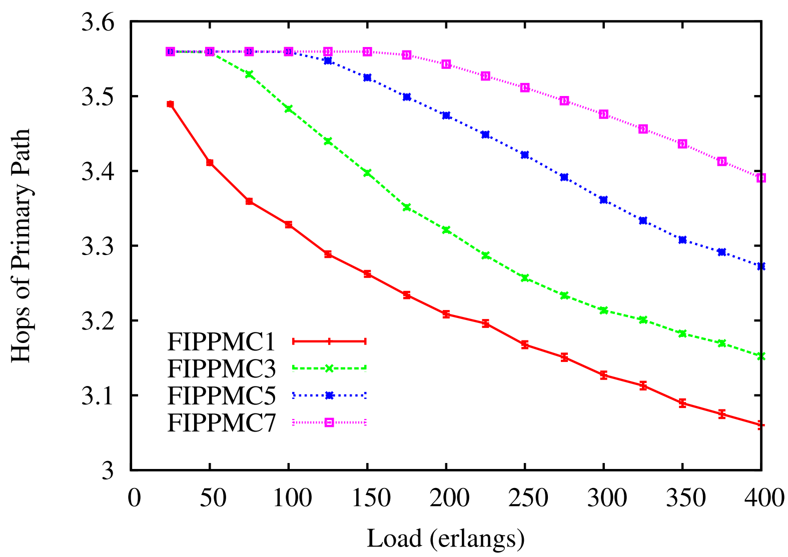


Figure 11: Average number of hops allocated per primary path for NSF topology

Figure 10 displays the Jain Fairness Index (JFI) of the BBR for different source destination pairs for the NSF topology. The FIPPMC algorithm in SCF blocking has high Jain index values, due to the high blocking, distributing blocked requests more uniformly among the source destination pairs. FIPPMC algorithm in 3MCF, 5MCF and 7MCF produce low Jain Index of fairness since several source destination pairs do not experience blocking, especially under low loads.

Figures 11 shows the average number of hops of the primary paths established for the NSF topology. As both the load and the BBR increase (as a consequence of the decrease of the average number of hops allocated per primary path), only short paths can be allocated. The blocking produced in this topology affects the capacity of establishing paths with arbitrary length. For 7MCF such capacity is not much affected by the load increase, however for SCF and 3MCF the impact is clearly pronounced.

5 Conclusion

The approach presented in this paper should provide a first step in protection of space division multiplexing elastic optical networks. This paper introduced an algorithm to support the establishment of lightpaths in elastic optical networks with multicore fibers protected by FIPP p-cycles. The algorithm was evaluated for different topologies and loads. Results indicate that the proposed algorithm can provide efficiently pre-configured protection for SDM in MCF networks. The node degree in a network topology has great influence in the bandwidth blocking ratio and on the length of established paths of protected networks, as showed by results using simulation.

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