Routing, Spectrum, Core and Modulation Level Assignment Algorithm for Protected SDM Optical Networks

Helder M. N. S. Oliveira and Nelson L. S. da Fonseca
Institute of Computing - State University of Campinas, Brazil
Email: helder@lrc.ic.unicamp.br, nfonseca@ic.unicamp.br

***Abstract*—The introduction of space division multiplexing (SDM) is a promising solution to cope with the ever increasing Internet traffic. The introduction of SDM brings new challenges for protecting the network since a lightpath can span multiple cores. In this paper, we propose a novel routing, modulation level and spectrum assignment (RMLSA) algorithm to dynamically generate primary and backup paths using a shared backup scheme and adaptive modulation in elastic optical networks employing multi-core fibers and space division multiplexing. The proposed algorithm is evaluated and its performance compared to the performance of other algorithms in the literature. Results indicate that 100% protection for single failures is achieved by our algorithm and yet it produces better performance when compared to the performance of existing algorithms.**

***Index Terms*—Protection, Multi-core Fiber, Elastic Optical Network with Space Division Multiplexing.**

I. Introduction

The increasing demand of bandwidth and the rapid approaching capacity limitation of single-core optical fibers has led to the exploitation of space to increase the network capacity. Space division multiplexing (SDM) involves using spatial channels and can be realized by using multimode fiber (MMF), multicore Fiber (MCF) or few-mode multicore fiber. In MMF, the number of modes supported by a fiber depends on the core size and on 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, modulation level and spectrum assignment (RMLSA) is a fundamental problem in the design of elastic optical networks (EON). RMLSA algorithms assign continuous and contiguous slots on all links of the selected route using modulation. The inclusion of the space degree of freedom adds another dimension to the RMLSA problem becoming the routing, modulation level, spectrum and core assignment (RMLCSA) problem. With the employment of a third dimension, the transmission capacity could increase several times as each core can be considered as an individual channel. On the other hand, MCF produces physical impairments that reduces the spectrum usability.

Although algorithms for spectrum and core allocation have been proposed [1]–[5], no other study related to protection in SDM elastic optical networks using modulation has been proposed so far. Protection is of paramount importance in optical transport networks that carry huge amount of traffic. Given the enormous capacity of an optical fiber employing SDM, any disruption implies on huge loss of data. As the carried traffic increases, the need for adoption of efficient protection schemes also increases. Such vulnerability motivated the development of different protection and restoration schemes for elastic optical network employing single core fiber (SCF).

Shared-backup path protection (SBPP) is one protection techniques which has been intensively investigated in the last decade due to the efficient sharing of spare capacity as well as flexibility in service provisioning. In EONs employing SDM, the SBPP employs a 1:N protection scheme in which backup paths can use the same set of spectrum (slots), provided that their corresponding working paths are link-disjoint.

TABLE I: Modulation Characteristics

Modulation Format	Bits per Symbol	Slot Capacity (Gb/s)	Maximum Distance (km)
64QAM	6	75	125
32QAM	5	62.5	250
16QAM	4	50	500
8QAM	3	37.5	1000
QPSK	2	25	2000
BPSK	1	12.5	4000

The OFDM technology for optical fiber gives the choice of the number of modulated bits per symbol (or modulation format) that can be realized using the same transponder [6]. Since the quality of transmission (QoT) of the connection depends directly on the transmission distance, the modulation format adopted should be distance adaptive, i.e., it should take into account the distance between source and destination. In this method, the most efficient modulation format from the use of spectral point of view is selected in a way that the path length does not exceed the transmission capacity. We adopted modulation formats shown in Table I [7] [8].

This paper introduces an algorithm called BAckuping, Routing, specTrum, coRe and Modulation level AssigNment (BARTRMAN) for providing shared protection in SDM-EONs using different modulation formats. The BARTRMAN algorithm uses backup paths interleaved with primary paths in order to generate less crosstalk per slot. It employs a Routing

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and Spectrum Assignment algorithm based on a multigraph representation of the spectrum. Results show that the proposed algorithm promotes protection effectively without significantly compromising blocking.

This rest of the paper is organized as follow. Section II reviews related work. Section III introduces the proposed algorithm. Section IV evaluates the performance of the proposed algorithm and Section V concludes the paper.

II. Related Work

The emergence of spacial division elastic optical networks has motivated several investigations, mainly on Routing, Spectrum and Core Assignment (RSCA) algorithms but only recently attention has been given to protection.

The authors in [1] presented a new virtual optical network (VON) provisioning procedure that is specifically designed for SDM-ONs using few mode fibers (FMFs). The impact of mode-dependent loss and the impact of network topology on VON provisioning are investigated based on an analytical model. In [9], the research progress on SDM fibers and network components is reviewed. A quantitative evaluation of technologies such as amplifiers, fan-in/fan-out multiplexers, transmitters, switches, and SDM nodes were introduced. Winzer *et al.* [10] investigated the basic operation and the achievable capacities of reliable optical MIMO-SDM transport systems in the linear transmission regime, focusing on the role of key system elements and the impact of their characteristics on MIMO-SDM performance. Hirota et.al. [2] divides the RSCA problem into the routing and core assignment (SCA) problems, and introduces a K-shortest path based pre-computation method as the routing solution. They proposed SCA crosstalk aware algorithms. In [3], a routing, spectrum and core allocation (RSCA) problem for elastic optical networks is proposed for network planning problem using integer linear programming (ILP) formulation as well a heuristic. In [4], an RSCMA solution is introduced which divided the problem into a routing and an SCMA problems. A pre-computation method based on the K-shortest path was introduced as the routing solution. The authors in [11] presented results from the first demonstration of a fully integrated SDN-controlled bandwidth-flexible and programmable SDM optical network utilizing sliceable self-homodyne spatial superchannels to support dynamic bandwidth and QoT provisioning, infrastructure slicing and isolation. In [5], it is proposed a scheme based on Failure-independent path protecting (FIPP) p-cycle for protection of elastic SDM optical networks. In [12], a novel algorithm is introduced for providing Failure-independent path protecting p-cycle with minimum interference for path protection in elastic optical networks using space division multiplexing. However, modulation was not considered.

III. The Algorithm

The algorithm introduced in this subsection, called BAckuping, Routing, specTum, coRe and Modulation level AssigNment (BARTRMAN), decides on the establishment of lightpaths in protected networks. A lightpath is established if and only if it can be protected by a shared path. The algorithm can use different modulation formats, depending on the distance between source and destination.

The proposed algorithm models the spectrum availability in the network as labeled multigraph (Fig. 1a). A label on an edge represents the availability of a slot. In Fig. 1b, the multigraph is divides into C multigraphs, where C is the number of cores. Each of these multigraphs is transformed into multigraphs with $N - b_m + 1$ edges, (Fig. 1c) where b_m is the bandwidth demand in slot according to the modulation format chosen. Then, each of these multigraphs is transformed into $N - b_m + 1$ graphs. In other words, the original multigraph (Fig. 1c) is transformed into $C \times (N - b_m + 1)$ graphs (Fig. 1d). Each edges in these graphs represents a combination of b_m slots. This representation assures spectrum contiguity to the solution. In these graphs, (Fig. 1d) an ∞ label value means that at least one slots is already allocated whereas the value 1 means that all slots are available for allocation.

A. Notation

The following notation will be used to describe the algorithm:

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 n^{th} edges connecting u and v;

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

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

$m = 1...M$: modulation formats (Table I);

b_m: bandwidth demand in slots taking into account modulation format to be adopted [8];

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

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

$w(e_{u,v,n})$: weight of the edge $e_{u,v,n}$; $w(e_{u,v,n}) = 1$ if the n^{th} slot in the link connecting OXC u and v is free and $w(e_{u,v,n}) = \infty$ if the slot is already allocated;

$W = \{w(e_{u,v,n})\}$:set of edge weights

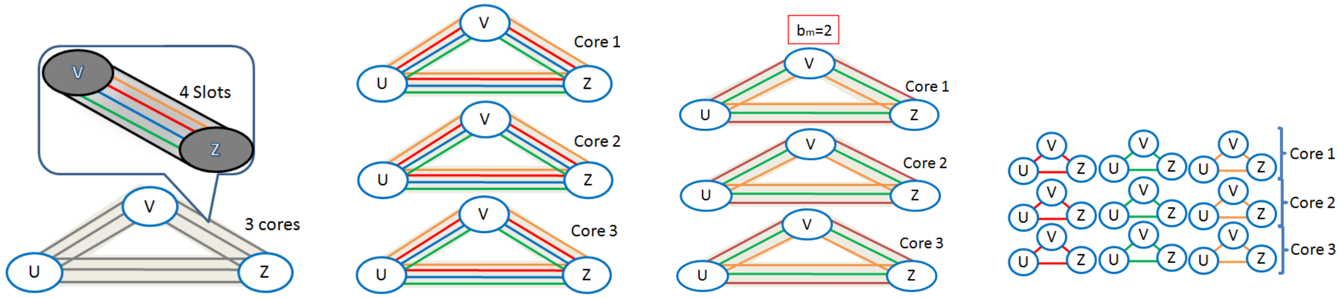
$\widetilde{V} = V$: set of nodes;

$\widetilde{e}_{u,v} \in \widetilde{E}$: edge connecting $\widetilde{u}$ and $\widetilde{v}$;

$\widetilde{e}_{\widetilde{u,v}} = \{e_{u,v,n}\} \in E$ is a chain such that $e_{u,v,n}$ is the least ordered edge, $e_{u,v,n+b_m}$ is the greatest ordered edge and $|\widetilde{e}_{u,v}| = b_m$;

$\widetilde{w}_n(\widetilde{e}_{\widetilde{u,v}})$: weight of the edge $\widetilde{e}_{\widetilde{u,v}}$;

$\widetilde{W} = \widetilde{w}_n(\widetilde{e}_{\widetilde{u,v}})$;



(a) Network with 3 cores and 4 slots.

(b) The Multigraph, separated by cores, each one representing 4 slots.

(c) The Multigraph in that set edges are mapped in to one edge, contiguity constraint.

(d) Graphs generated.

Fig. 1: Transforming multigraph in graphs

$\widetilde{G}_{n,b_m} = (\widetilde{V}, \widetilde{E}, \widetilde{W})$: 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_m edges in G starting at the $n^{th} edge$;

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

$\tau(G, C, b_m) = \{\widetilde{G}_{n,b_m}\}$: function which produces all σ graphs from G;

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

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

$W_{P_{s,d}}$ = weight of the shortest path between s and d;

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

$T_{u,v}$: set of all backup path between vertices u and v in G;

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

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

$\xi(\widetilde{G}_{n,b_m}, P_n, r(s, d, b))$: shortest path between s and d in $\widetilde{G}_{n,b_m}$, which it and $P_{T_{s,d}}$ are link disjoint to P_n;

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

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

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

B. BARTRMAN

The algorithm BARTRMAN is introduced in Algorithm 1. Line 1 transforms the multigraph into $C \times (N - b_m + 1)$ graphs. Line 2 computes the shortest path for all graph $\widetilde{G}_{n,b_m}$ and choses the least costs one. If the weight of the shortest path is ∞, it was not possible to find a path under the contiguity constraint for the demand b. Line 3 selects the path among all shortest paths that has the lowest weight value. In case the weight of all shortest path is ∞ (Line 4), there is no path in the network that satisfies the request of b_m slots under the contiguity constraint. If there is no path available then the request is blocked (Line 5). Otherwise, another path to protect this lightpath to be established is searched (Line 7). In case there exists a path, the lightpath is established (Line 8) and the corresponding edges in the multigraph G have their weight changed to ∞ (Line 9) meaning that the slots were allocated to the newly established lightpath. Otherwise, a path to protect the lightpath to be established should be created (Line 12). In case no path can be created to protect the lightpath then the request is blocked (Line 15). Otherwise, the primary path as well as the backup path (Line 17) are established to satisfy the request and the corresponding edges in the multigraph G have their weight changed to ∞ (Lines 18 and 19) meaning that the slots were allocated to the newly established lightpath.

Algorithm 1 BARTRMAN

```
1:  τ(G, C, b_m)   ∀m ∈ M
2:    (W(P_n), P_n) = δ(G̃_{n,b_m}, r(s, d, b))   ∀n ∈ σ
3:      W_{P_{s,d}} = W(P_n)| ∀i W(P_n) ≤ W(P_i)
4:  if  W_{P_{s,d}} = ∞ then
5:    block r(s, d, b)
6:  else
7:    if ∃μ(P_n, T_{s,d}, r(s, d, b)) then
8:      establish r(s, d, b) as P_n and T_{s,d}
9:      W(ẽ_{u,v,i}) = ∞   ∀{u, v} ∈ P_i
10:   else
11:     τ(G, C, b_m)   ∀m ∈ M
12:       (W(T_n), T_n) = ξ (G̃_{n,b_m}, P_n, r(s, d, b))   ∀n
13:       W_{T_{s,d}} = W(T_n)| ∀i W(T_n) ≤ W(T_i)
14:     if  W_{T_{s,d}} = ∞ then
15:       block r(s, d, b)
16:     else
17:       establish r(s, d, b) as P_n and T_n
18:       W(ẽ_{u,v,i}) = ∞   ∀{u, v} ∈ P_i
19:       W(ẽ_{u,v,i}) = ∞   ∀{u, v} ∈ T_i
20:     end if
21:   end if
22: end if
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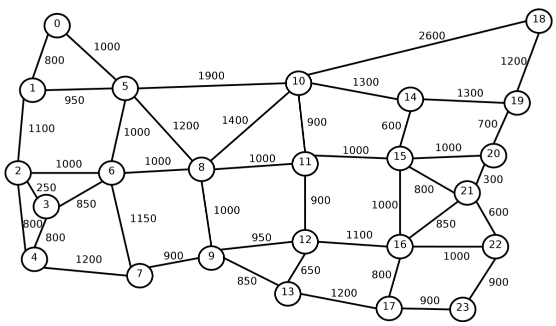
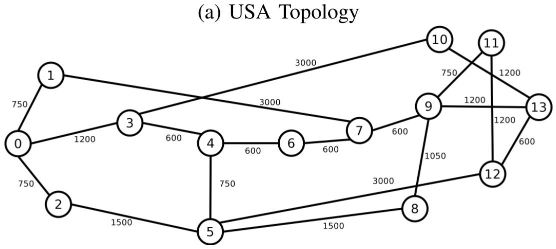
The complexity of the BARTRMAN algorithm is analyzed as follows. The complexity of transforming the original multigraph in graphs is $O(E + V)$. In the worst case, Dijkstra's algorithm is executed in $C \times N - b_m$ graphs for M different set of graphs, $O(E + V + (M \times C \times N \times (\|E\| + \|V\| \times log\|V\|)))$, since M, C and N values can be expressed as constant, then the complexity is: $O(\|E\| + \|V\|log\|V\|)$.

IV. Performance Evaluation

To assess the performance of the BARTRMAN algorithm in multi-core networks, simulation experiments were employed. The FlexGridSim [13] simulator was employed. In each simulation, 100,000 requests were generated as input and simulations for all the algorithms used the same set of seeds. Three types of requests were employed 125 Gbps, 400 Gbps and 1 Tbps. The links were composed by MCFs with 7 core and each core was divided in 320 slots. Confidence intervals were derived using the independent replication method with 95% confidence level. Requests follows a Poisson process and are uniformly-distributed among all node-pairs of network. The topology used in the simulations were the USA (Fig. 2a) and the NSF (Fig. 2b) topologies. The NSF topology has 16 nodes and 25 links whereas the USA topology has 24 nodes and 43 links (Fig. 2). The numbers on the links represent the length of the link in kilometers.



(a) USA Topology



(b) NSF Topology

Fig. 2: Topologies

In the figures, the curves labeled “BPPM" show the results for networks using protection 1:1 and shortest path algorithm, the curves labeled “FIPPMC" show the results for networks using the algorithm FIPPMC [5]. The curves labeled "SS-CAM" show the results for networks using the algorithm based on the methods proposed in [2] which uses a K-shortest paths algorithm to compute routes; we use K = 3. The curves labeled “BARTRMAN" display the results for networks using the proposed BARTRMAN algorithm. The algorithms BPPM, BARTRMAN and SSCAM use adaptative modulation, while FIPPMC algorithm does not.

The FIPPMC decides on the establishment of lightpaths in an FIPP p-cycle protected network. In the SSCAM and BPPM algorithms, the primary path is treated independently, i.e., the routing problem and the SCA problem considering the distance between source and destination. 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.

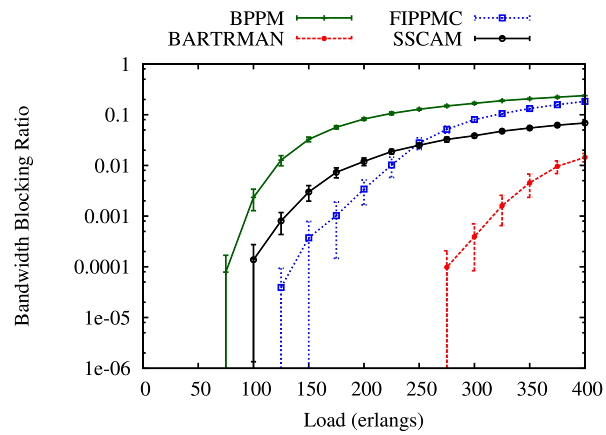


Fig. 3: Bandwidth blocking ratio for the USA topology

Fig. 3 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA topology. While BPPM starts blocking requests under loads of 75 erlangs, SSCAM and FIPPMC start blocking only under loads of 100 and 125 erlangs, respectively. The BARTRMAN starts blocking request only under loads of 250 erlangs. Until loads of 250 erlangs, the difference between the BBR produced by the SSCAM algorithm and that given by the FIPPMC algorithm is almost one order of magnitude. Under high loads of 275 erlangs, the difference between the BBR produced by the BARTRMAN algorithm and those given by the other algorithms is almost three order of magnitude and almost four orders of magnitude when compared to that produced by BPPM. Such BBR values produced by BARTRMAN evinces the benefit of jointly choosing the route and the core to provide protection when compared to choosing them in different steps as done by the SSCAM algorithm. These results show that the BARTRMAN algorithm produces acceptable blocking for multi core fibers with SDM.

The use of seven cores generates intercore crosstalk. Fig. 4 shows the “Crosstalk per Slot” (CpS) as a function of the load for the USA topology. The crosstalk value for each spectrum slot is defined as the ratio of actual crosstalk index to the maximum value of crosstalk index. The crosstalk ratio is defined by the average value among all spectrum slots [14]. The CpS is not considered when the slot is reserved but not used. The generated CpS for the SSCAM and BPPM algorithms start at 0.019 and 0.018 and increase until 0.15 and 0.37, respectively. The generated CpS for the FIPPMC algorithm starting at 0.014 and increases until 0.41. The generated CpS for the BARTRMAN starts at 0.007 and increases until 0.14. The CpS produced by FIPPMC is higher than that produced by the other three algorithms as a consequence of not employing adaptive modulation. Besides the BARTRMAN algorithm producing

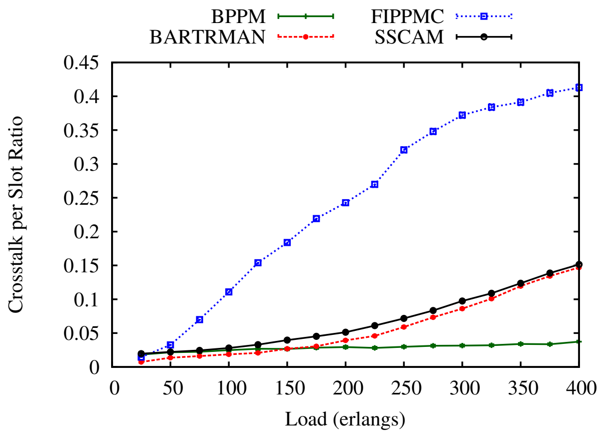


Fig. 4: Crosstalk per slot ratio for the USA topology

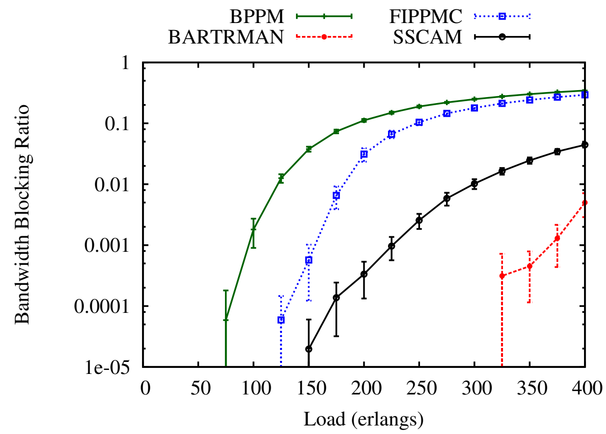


Fig. 6: Bandwidth blocking ratio for the NSF topology

low blocking and high utilization, it also produces CpS values lower than the ones produced by FIPPMC and SSCAM, as a consequence of the interleaved use of cores for primary and backup paths decreasing the CpS generated.

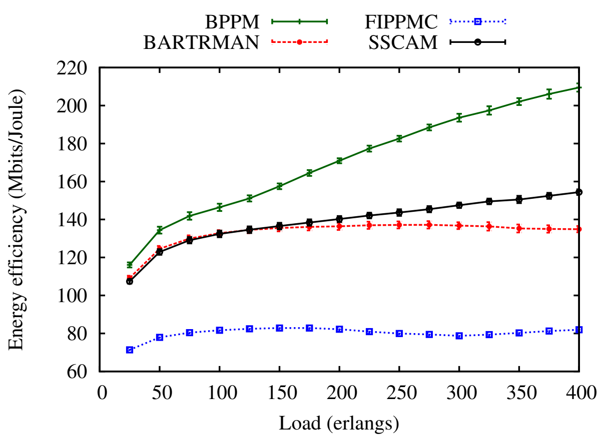


Fig. 5: Energy Efficiency for the USA topology

Fig. 5 shows the energy efficiency as a function of the load for the USA topology. The energy efficiency is obtained by dividing the total traffic demand successfully served in the network by the total power consumption [15]. The BPPM produces the highest energy efficiency as a consequence of the allocation of short paths, i.e. the blocking produced in this topology affects the capacity of establishment of paths with arbitrary length. The FIPPMC produces the lowest energy efficiency as a consequence of not using adaptive modulation. There is not much difference between the energy efficiency of SSCAM and BARTRMAN. The difference arises only under heavy load, despite BARTRMAN producing significantly lower blocking ratios under these loads.

Fig. 6 shows the bandwidth blocking ratio (BBR) as a function of the load for the NSF topology. While BPPM starts blocking requests under loads of 75 erlangs, SSCAM and FIPPMC start blocking only under loads of 125 and 150 erlangs, respectively. The BARTRMAN starts blocking request only under loads of 325 erlangs. Until loads of 175 erlangs, the difference between the BBR produced by the BPPM algorithm and that given by the FIPPMC algorithm is almost two order of magnitude. Under high loads of 325 erlangs the difference between the BBR produced by the BARTRMAN algorithm and that given by SSCAM algorithms is almost two order of magnitude and it is almost three order when compared to that produced by the other algorithms. Such BBR values produced by BARTRMAN evinces the benefit of choosing jointly the route, core and modulation when compared to choosing them in different steps.

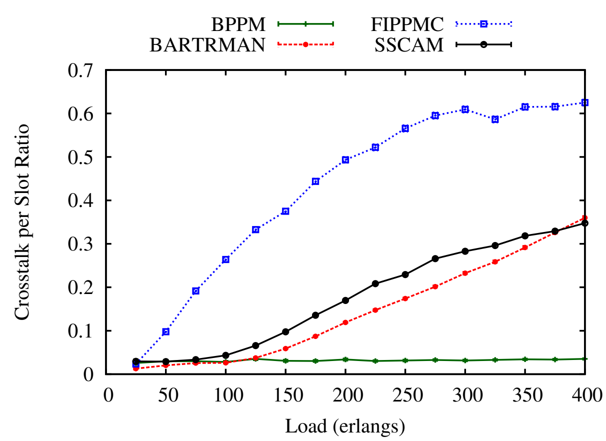


Fig. 7: Crosstalk per slot ratio for the NSF topology

Fig. 7 shows the crosstalk per slot (CpS) as a function of the load for the NSF topology. The generated CpS for the SSCAM and BPPM algorithms start at 0.029 and 0.025 and increase until 0.34 and 0.035, respectively. The generated CpS for the FIPPMC algorithm starts at 0.023 and increases until 0.62. The generated CpS for the BARTRMAN starts at 0.012 and increases until 0.36. The CpS produced by FIPPMC is higher than that the CpS produced by the other three algorithms, because this algorithm does not employ adaptive modulation. As in the USA topology, besides the BARTRMAN algorithm producing low blocking and high utilization, it also produces lower CpS than the CpS produced by SSCAM and FIPPMC. The interleaved use of cores for primary and backup paths decreases the CpS generated.

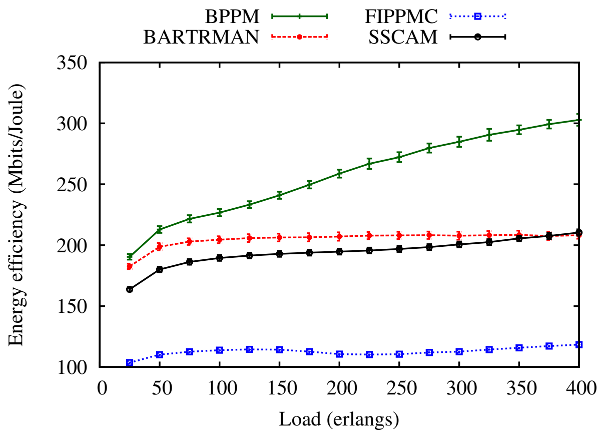


Fig. 8: Energy Efficiency for the NSF topology

Fig. 8 shows the energy efficiency as a function of the load for the NSF topology. The BPPM produces the highest energy efficiency as a consequence of producing high BBR values, only short paths can be allocated, i.e. the blocking produced in this topology affects the capacity of establishing paths with arbitrary length. The FIPPMC produces the lowest energy efficiency as a consequence of not employing adaptive modulation. Differently than the results for the USA topology, the energy efficiency produced by BARTRMAN is higher than that produced by the SSCAM algorithm.

V. Conclusion

This paper introduced an algorithm to address the RSCMA and protection problem. We have proposed a novel approach to support the establishment of lightpaths in spacial division multiplexing elastic optical networks protected by shared backup paths using adaptive modulation. The algorithm was evaluated for different topologies and loads. BARTRMAN was compared to other algorithms using adaptive modulation and the FIPPMC algorithm which does not employ adaptive modulation. Simulation results evinces the better performance of the BARTRMAN algorithm when compared to the other evaluated algorithms.

Acknowledgments

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