Crosstalk and Fragmentation-aware Algorithm for Space-Division Multiplexing Elastic Optical Networks

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***Abstract*—Optical fiber is the most adopted communication technology on the Internet backbone. However, it is expected that the transmission capacity of the existing optical fiber will reach its physical limitation due to the growing increase of bandwidth demand. The Space-Division Multiplexing Elastic Optical Networks has shown to be a quite promising technology to solve this problem due to its capacity expansion and requests adjustment properties. This paper proposes an RMSCA algorithm for SDM-EONs, focusing on reducing the blocking ratio and dealing with crosstalk and fragmentation. Results indicate that our algorithm provides 10% of reducing of blocking, yet it produces better performance compared to the performance of existing algorithms.**

***Index Terms*—Crosstalk, Elastic Optical Networks, Fragmentation, Space Division Multiplexing, Routing.**

I. INTRODUCTION

Global traffic is increasing at a rate of 60% per year [1]. Moreover, the explosive growth in global data consumption puts enormous pressure on telecommunications. Fiber-based networks constitute essential segments of telecom infrastructure, being responsible for connecting millions of internet users. A massive amount of data, audio, and video traffic is transmitted, downloaded, and exchanged daily through these networks. As the demand for bandwidth increases, driven mainly by the rapid expansion of connected devices and the growth of cloud-based services and applications, the need for faster and reliable connections become mandatory. However, most of fiber based infrastructure employ single-mode fiber with limited capacity which tends to be insufficient in the near future to cope with the intense traffic growth.

Conventional single-mode fibers have served as a reliable means of transmission for the past 30 years, enabling network operators to keep pace with increased data traffic through a sequence of technical innovations associated with the increasing growth of fiber transmission capacity [2]. However, it is widely recognized that the maximum transmission capacity of a single-mode fiber is rapidly approaching its fundamental data transport limit, a partial consequence of the fiber's nonlinearity and the bandwidth of fiber amplifiers [3]. Increasing the number of fibers is a solution, but it imply a high cost and requires significant energy consumption. Recently, SDM (Space-Division Multiplexing) technology has attracted the attention since it is a promising technology to significantly increase the transmission capacity of the fiber and reduce the total cost per bit transmitted [4].

One of the strategies used to accommodate the growth of data traffic is the employment of EON (Elastic Optical Networks) that provides fine granularity for spectrum allocation, contributing to the reduction bandwidth wastage. Combined with the capacity expansion given by SDM technology, SDM-EON (Space-Division Multiplexing Elastic Optical Networks) has become as an interesting solution to meet future transport requirements [5]. The emergence of SDM networks has risen new challenges for resource management due to the increased complexity caused by the use of multi-core fibers.

In SDM-EON network, the Routing, Spectrum, and Core Allocation (RSCA) problem refers to the allocation of the network spectrum. The RSCA is solved by the selection of the core to be used, under the observation of the maintenance of the continuity and contiguity constraints. These constraints ensure that transmissions occur on a single nucleus along the entire route, and that the slots allocated for the request must be contiguous [6]. In addition, the employment of adaptive modulation allows the selection of the highest possible number of bits per transmission [7]. The RSCA problem is extended to include the selection of a modulation scheme becoming the Routing, Modulation, Spectrum, and Core Allocation (RMSCA) problem.

Moreover, two other issues need to be carefully addressed: crosstalk between cores and fragmentation. Crosstalk is the interference that occurs in multi-core fibers due to simultaneous transmissions in adjacent cores using the same frequency slot. This interference degrades the signal, compromising the transmission. Fragmentation is the configuration of the spectrum allocation resulting from the dynamics of allocation and tear down lightpaths. The spectrum made available after the

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tear down of a lightpath may not be sufficient for establishing incoming requests.

This paper proposes a Crosstalk and Fragmentation-aware Routing, Modulation, Spectrum, and Core Allocation, called RUPERT. RUPERT aiming at reducing the crosstalk and fragmentation levels acceptable under different loads. The spectrum allocation strategy finds paths that can provide bandwidth for the lightpaths request, considering the existing and generated crosstalk and fragmentation, reducing the impact on established lightpaths and the acceptance of incoming lightpaths requests. Results show that RUPERT's bandwidth blocking ratio is the lowest among the compared algorithms while CpS is adequate even with more established lightpaths.

The remainder of this paper is organized as follows. Section II outlines the state-of-the-art space-division multiplexing EON. Section III describes the RUPERT algorithm. Section IV discusses the simulation description and results. Finally, Section V introduces the conclusions.

II. RELATED WORKS

SDM-EON has motivated research on the development of mechanisms that promote the use of network resources more efficiently by controlling the fragmentation and crosstalk. However, few papers have considered these two issues together.

The work in [8] proposed three algorithms to ameliorate the fragmentation problem and reduce the blocking of requests. The algorithms seeks in available spectrum rectangular regions to allocate a lightpath using the K-Shortest Paths algorithm, making into account the existing fragmentation. The proposed algorithms do not employ adaptive modulation.

The authors in [9] proposed a scheme to decrease fragmentation and increase the number of transmissions in the network. The scheme seeks for a path using the K-Shortest Paths algorithm and the FirstFit (FF) allocation policy, but does not consider spatial division multiplexing and it employs just a single modulation for transmissions.

Moghaddam *et. al.* [10] introduced a Mixed Integer Linear Programming (ILP) and a heuristic to deal with crosstalk and scheduling problems. They considered static traffic and routes previously computed by the K-shortest path algorithm. The mixed ILP ensures that only one path is allocated to each request, then adaptive modulation is applied, and the crosstalk intensity is calculated for each slot in the spectrum. The best modulation is selected to mitigate signal degradation and crosstalk interference. However, the authors did not use any strategy to reduce fragmentation.

Xiong *et. al.* [11] used machine learning techniques to mitigate fragmentation and crosstalk in SDM-EON. A neural network was used to predict the bandwidth, and a mechanism for visualizing the network spectrum in two-dimension for resource allocation was also employed. The work proposes a strategy to deal with fragmentation, however, it does not consider adaptive modulation to better use the spectrum.

The authors in [12] developed three algorithms to deal with crosstalk, maintain the level of security of the physical layer, and reduce the likelihood of blocking. The authors consider the interference caused by crosstalk between cores. There is an attempt to control the likelihood of blocking by preventing fragmentation and crosstalk. The ExactFit algorithm is used to find free spaces in the spectrum that can allocate the exact number of slots requested. The MINCROSS algorithm prioritizes the reduction of crosstalk, MINFRAG prioritizes the reduction of fragmentation, while MODFRAGCROSS seeks to balance crosstalk and fragmentation.

Based on our analysis of the state-of-the-art, we conclude that the RMSCA problem is still an open issue since none of the reported work considers all critical characteristics previously mentioned.

III. RUPERT ALGORITHM

This section introduces Routing, modUlation sPEctrum, and core allocation with cRosstalk and fragmenTation aware. (RUPERT) algorithm. In this algorithm, a full network scan is performed, then the available resources are separated into sets, and thus the impact on crosstalk and fragmentation is measured, then light paths can be established. Furthermore, six different modulation levels are considered in the algorithm, taking into account the total transmission distance to choose the modulation. In RUPERT, we find the route first, then we allocate core and slots, keeping the continuity and contiguity constraints and controlling the fragmentation and crosstalk levels, keeping them acceptable.

A. Network Overview

The optical network operates with spatially flexible reconfigurable optical add/drop multiplexers that allow wavelength-selective switch, and space-wavelength granularity, with multiple-input multiple-output (MIMO) transceivers.

We consider that the network is composed of MCF links with seven cores arranged in a hexagonal array, and each one has a spectrum availability of 320 frequency slots with 12.5 GHz of capacity. A pair of nodes with one bidirectional link is used, and the link length varies according to the distances in km. The network equipment does not allow the exchange of circuits between different cores, being necessary to maintain the restriction of core continuity. Besides that, the number of slots necessary to satisfy the bandwidth demands depends on the modulation level chosen. Paths are separated by an FGB (Filter Guard Band) represented by 1 slot.

We consider several modulation levels for path allocation. However, the connection Quality of Transmission (QoT) depends directly on the transmission distance and modulation level chosen, since the modulation level adopted must take into account the distance between source and destination. In this context, the most efficient modulation level is selected so that the path length does not compromise the transmission capacity. In this paper, we employ 64QAM, 32QAM, 16QAM, 8QAM, QPSK, and BPSK modulation formats for extensions of 125, 250, 500, 1000, 2000, and 4000 km respectively with slot capacities of 75, 62.5, 50, 37.5, 25, and 12.5 Gb/s.

B. RUPERT Algorithm Operations

The RUPERT is an RMSCA alorithm for SDM-EONs that can be employed for different loads, scenarios, and topologies. The algorithm aims at reducing the number of blocked requests and increasing the amount of data transmitted over the network. Fragmentation reduction is reduced by a mechanism that try to avoid spectrum wastage caused by the dynamic allocation and deallocation of resources, and it is parameterized by equation presented in [13].

Crosstalk is also reduced by the selection of slots that are less affected and cause less interference in neighbors, and it is calculated by the Crosstalk per Slots (CpS). The algorithm does not allow the core switching, which prevents signal conversion from optical to electrical, helping to obey the continuity and contiguity constraints. A full network scan is performed in the algorithm and the spectrum is mapped to a set of matrices, representing the resources that can accommodate the request. The algorithm receives the traffic as input and returns the possible lightpath with enough resources to host the request. Table I shows the notation that will be used to describe the algorithm.

TABLE I
NOTATION

Notation	Definition
s	Source node
d	Destination node
b	Demand in slots
$e \in E$	Link from the network
$v \in V$	Node from the network
$C \in C$	Core from the network
$s \in S$	Slot from the network
$r(s,d,b)$	Request from s to d with bandwidth demand of b
$m \in M$	The set of modulations $M = \{1,2,3,4,5,6\}$
$g(v,e,c,s)$	A virtual graph that maps the slot s across the network
$G = \{g(v,e,c,s)\}$	The set of virtual graphs
$p \in P$	Path for each request
Map_{cs}	Map Matrix for each fiber link
b_m	Number of slots required for transmission according to the modulation applied
f	Fragmentation
cr	Crosstalk

The RUPERT algorithm is introduced in Algorithm 1. Information about the physical topology, modulations, and requests, with information about the source and destination nodes and bandwidth, makes the input to the routing process. In Line 1, modulations are tested until a path is found. In Line 2, the total amount of slots are calculated according to the number of bits that can be transmitted according to the modulation chosen. In Line 3, the Mapping algorithm is called with information on the physical characteristics of the network topology and demands as parameters. The output is a set of graphs generated, employed for the process of finding the shortest available path for transmission. In Line 4, for each graph, the shortest path is found, fragmentation and crosstalk are calculated and these values are stored for future use. In Line 9, the shortest path with lowest fragmentation and crosstalk levels is selected and the request accepted. In the case no path is found the request is blocked (Line 15).

Algorithm 1: RUPERT

```
Input  : $r(s,d,b)$, $V, E, C, S, M$
Output: Lightpath
1  for all $m \in M$ do
2      $b_m$: Estimate demand in slots for modulation;
3      $G$ = Mapping($V, E, C, S, b_m$);
4      for all $g \in G$ do
5          $P$: Find the shortest available path on mapped network;
6          $f$: Calculates fragmentation;
7          $cr$: Calculates crosstalk;
8      end
9      Select the shortest path $p$ with lowest $f$ and $cr$;
10     if $P \neq \phi$ then
11         Accept request;
12         return established path;
13     end
14 end
15 Block request;
16 return;
```

Algorithm 2: MAPPING

```
Input  : $V, E, C, S, d_m$
Output: Mapped network
1  for all $e \in E$ do
2      for all $c \in C$ do
3          for all $s \in S$ do
4              $Map_{cs}$: Binary Matrix Mapped;
5              if all $s + b_m$ slots are available then
6                  $Map_{cs}$ = True;
7              end
8              if $s + b_m$ aren't available then
9                  $Map_{cs}$ = False;
10             end
11             $G = g(v,e,c,s)$;
12         end
13     end
14 end
15 return G;
```

In Algorithm 2, the network spectrum is mapped in a binary matrix. Each slot is checked, moving on to all the edges, cores, and slots (in Lines 1 to 3), where a slot is marked as true if the sequence of slots scanned are available and can fit the request, otherwise, the slot is marked as false.

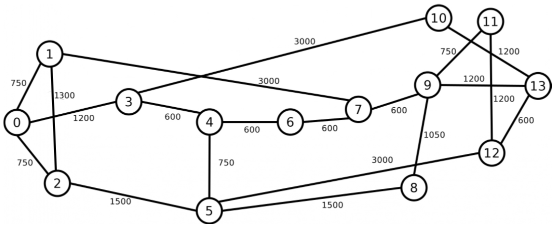
The complexity of the RUPERT algorithm is analyzed as follows: The complexity of mapping the network is $O(E+V)$. For a single path, in the worst case, the chosen modulation will be the one with the lowest spectral efficiency. In the worst case, to find the path, the Dijkstra algorithm runs M times, where Dijkstra's amortized complexity is $O(E + VlogV)$, obtaining a complexity of $O(E + VlogV)$.

IV. PERFORMANCE EVALUATION

This section describes the evaluation methodology, including simulation parameters, and metrics used to evaluate the performance of different RMSCA algorithms.

A. Scenario description and methodology

For performance analysis of the RMSCA algorithm, simulations were performed on SDM-EONs using the Flexgridsim [14] discrete event simulator. The generation of requests followed the Poisson process and was evenly distributed among the network nodes. At least ten simulations were replicated for each scenario. The network load varied between 50 and 1000 erlang, with 100,000 requests for each simulation made. Confidence intervals were generated using the replication method, with a confidence level of 95%. The same set of seeds was used for the different algorithms. Seven different types of requests were used with transmission rates of 25/50/125/200/500/750/1000 Gbps. The fiber has seven cores arranged in a hexagonal shape, with 320 frequency slots divided for each core. The topologies used in the simulations were the USA topology, 24 nodes and 43 links, and the NSF topology, with 14 nodes and 19 links (Figure 1). The number in the link represents the distance between nodes in kilometers.



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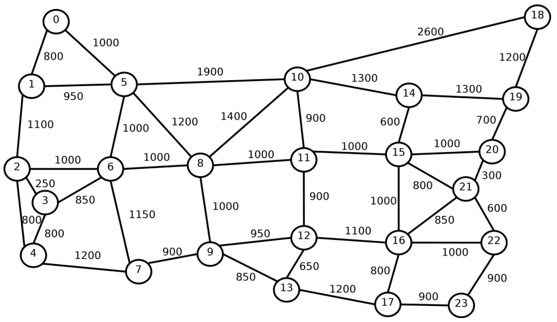

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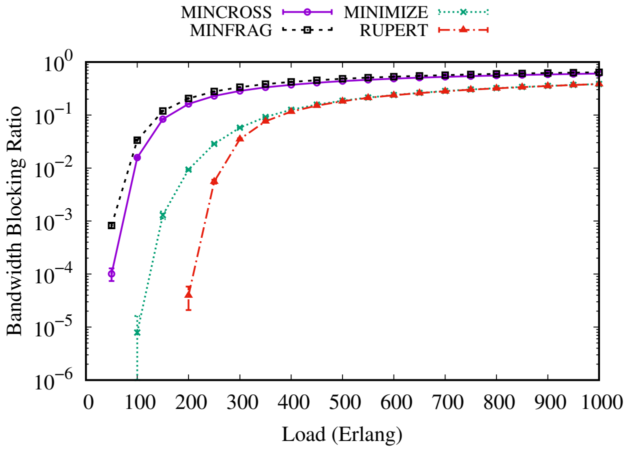
Fig. 1. Topologies

We compare the simulation results of the algorithm RUPERT with those given by MINCROSS [12], MINFRAG [12] and MINIMIZE [15]. Specifically, the MINCROSS algorithm employs the strategy of selecting the path with the lowest level of crosstalk. MINFRAG algorithm uses a similar strategy but selects the path with the lowest level of fragmentation. In the MINIMIZE algorithm, the routing problem is handled independently of the MSCA problem considering the distance between source and destination.

The metrics considered for evaluation of the algorithms are the Bandwidth Blocking Ratio (BBR), the Crosstalk per slot (CpS), and Energy Efficiency (EE). BBR is defined as the percentage of bandwidth (traffic) blocked over the total bandwidth requested during the entire simulation period. CpS is analyzed as the average ratio between the pairs of frequency slots used that have the same frequency and are located in adjacent cores (Arrangement of Crosstalk, AoC) and the total of slots used. Energy efficiency is calculated by dividing the total traffic demand successfully served in the network by the total power consumption.

B. Results

Figure 2 shows the results for bandwidth blocking ratio for the NSF and USA topologies, respectively. For NSF topology, while the MINIMIZE algorithm starts blocking requests under loads of 100 erlang, and the MINCROSS and MINFRAG algorithms under loads of 50 erlang. The RUPERT algorithm starts blocking requests only under loads of 200 erlang. Under higher load, the MINIMIZE and RUPERT algorithms produce similar results. However, for all loads simulated, the RUPERT algorithm produces the lowest blocking bandwidth ratio, thus, the RUPERT algorithm can transmit much more data than the other algorithms.



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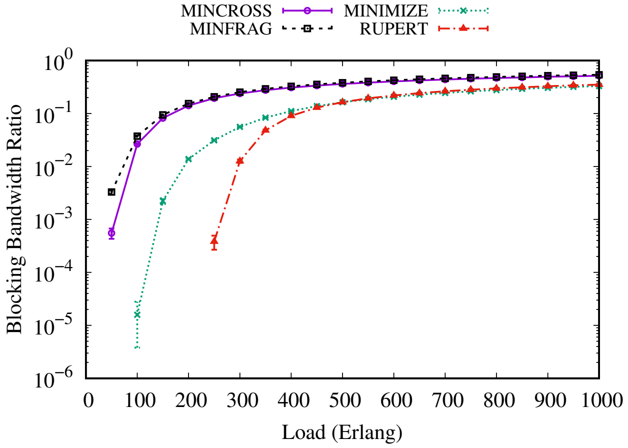

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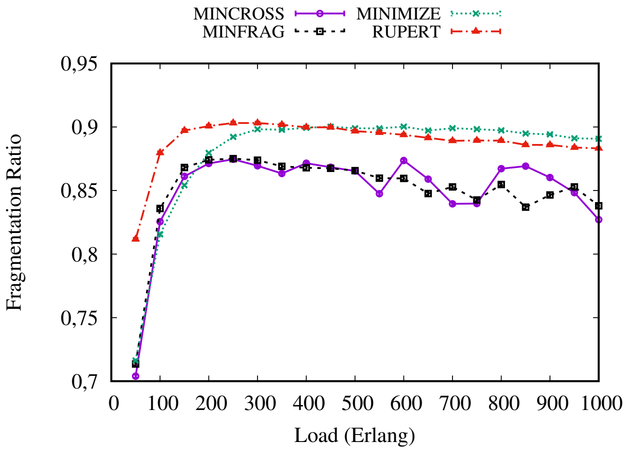
Fig. 2. Bandwidth blocking ratio

For the USA topology, the RUPERT algorithm starts blocking requests under loads of 250 erlang, while the MINIMIZE algorithm starts blocking requests under loads of 100 erlang and MINCROSS and MINFRAG start blocking requests under loads of 50 erlang. Until a load of 400 erlang, the RUPERT algorithm has the lowest BBR evincing the benefits of considering fragmentation and crosstalk -aware. Under high loads, the difference between the BBR produced by the RUPERT algorithm and those produced by the other algorithms is almost one order of magnitude. Results show that the proposed algorithm RUPERT promotes efficient resource allocation for both NSF and USA topologies, reducing the blocking ratio to acceptable levels.



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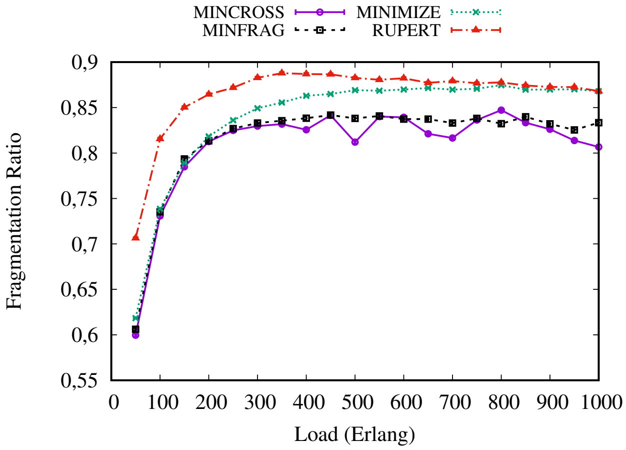

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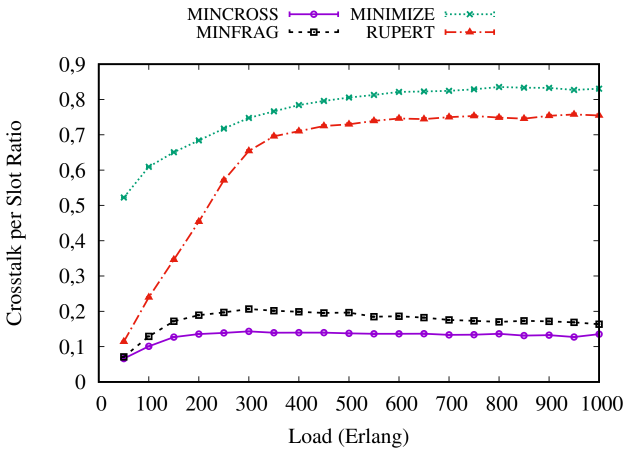
Fig. 3. Fragmentation ratio

Figure 3 shows the results for fragmentation ratio for the NSF and USA topologies. For the NSF topology, the MINCROSS, MINFRAG, and MINIMIZE algorithms produce less fragmentation than the RUPERT algorithm under loads up to 250 erlang. This is a consequence of the RUPERT algorithm accepting more connections under these loads. From loads of 250, the RUPERT algorithm produces less fragmentation than that does the MINIMIZE algorithm, maintaining the result for all simulated loads, while the MINCROSS and MINFRAG algorithms produce results numerically close which are lower than those produced by the other algorithms.

For the USA topology, the MINCROSS, MINFRAG and MINIMIZE algorithms produce results close to each other under lower loads up to 200 erlang, while the RUPERT algorithm produces higher fragmentation. This is a consequence of the RUPERT algorithm accepting more connections under these loads. Under loads higher than 700 erlang, the MINIMIZE and RUPERT algorithms show similar results, while the MINCROSS and MINFRAG algorithms produce less fragmentation. The MINCROSS and MINFRAG algorithms adopt similar routing strategies, with greater considerations for crosstalk and fragmentation, respectively, producing very similar results, while MINIMIZE combines other strategies for reducing fragmentation. The RUPERTalgorithm, on the other hand, seeks to reduce fragmentation as one of the mechanisms, coupled with the prevention of crosstalk.



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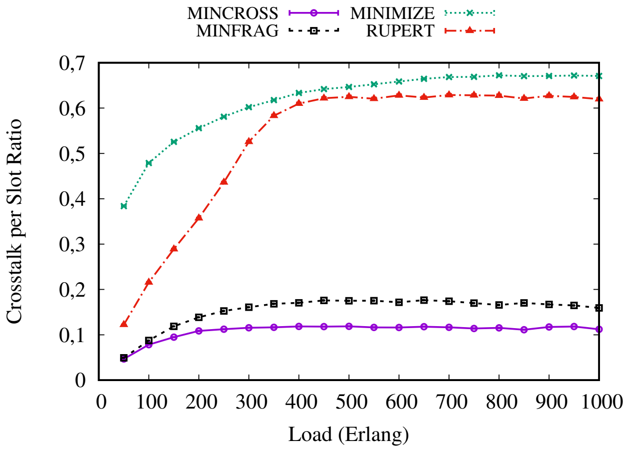
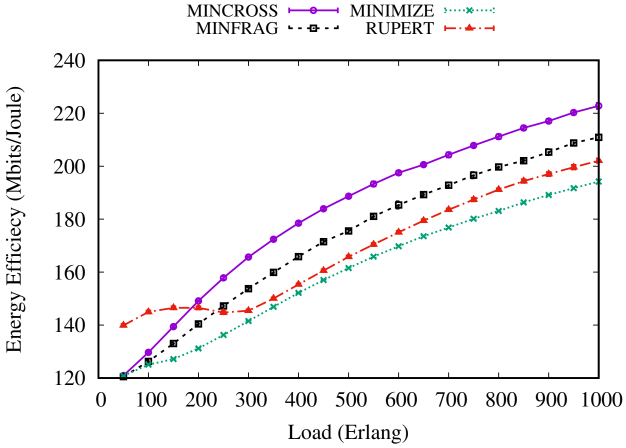


(b) USA

Fig. 4. Crosstalk per slot ratio

Figure 4 shows the crosstalk per slot for the NSF and USA topologies, respectively. For the NSF topology, the RUPERT algorithm produces intermediate crosstalk result per slot, between those produced by MINIMIZE and the other two algorithms for all simulated loads. For lower loads, the RUPERT algorithm produces crosstalk close to that given by the MINFRAG algorithm. However, there is an increase in

CpS, being closer to that produced by the MINIMIZE algorithm. For the USA topology, all algorithms produce results similar CpS, with the RUPERT algorithm having intermediate value among those produced by the other algorithms. The MINCROSS and MINFRAG alorithms produce the lowest CpS, and the MINIMIZE algorithm the highest one for all simulation loads.



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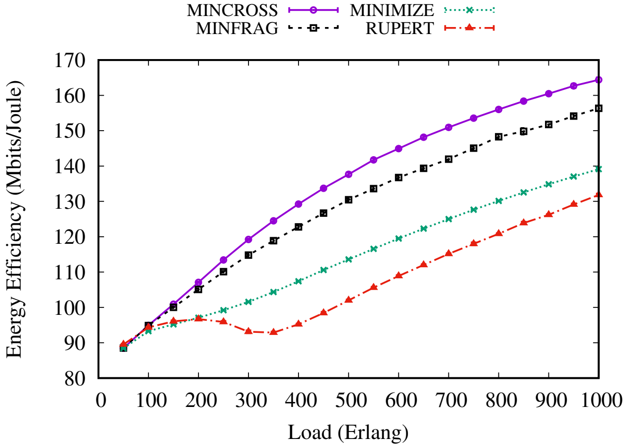

(b) USA

Fig. 5. Energy Efficiency

Figures 5(a) and 5(b) show the energy efficiency for the NSF and USA topologies, respectively. For NSF, under low load, the RUPERT algorithm presents the best efficiency, however, such efficiency is reduced under a load of 200 erlang, while the MINFRAG and MINCROSS algorithms are more efficient. The MINIMIZE algorithm produces the lowest energy efficiency. For the USA, the MINCROSS algorithm is the most energy-efficient, followed by MINFRAG, MINIMIZE, and RUPERT algorithms.

V. CONCLUSIONS

In this paper, we propose an algorithm called RUPERT, which aims at controlling the level of crosstalk and fragmentation as well reducing the blocking of requests. The algorithm was evaluated for different topologies and loads. Simulation results evince that the RUPERT algorithm reduces the BBR compared to other RMSCA algorithms investigated and provides an efficient allocation, producing good energy efficiency.

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