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

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Abstract—**Spatial division multiplexing is a promising solution proposed for elastic optical networks to cope with the expected depletion of the capacity of single core networks. The introduction of space division multiplexing in optical networks brings new challenges for network protection since a lightpath can span high capacity and transmit data at different rates. In addition, there is a great need for protection mechanisms against failure due to the high volume of traffic carried in these networks. Moreover, these networks suffer from the fragmentation of the spectrum that hampers the contiguity and continuity constraints and therefore increase blocking. To address these problems, in this paper, we propose a protection algorithm for elastic optical networks with spatial division multiplexing using hybrid routing and FIPP p-cycle. The proposed algorithm prioritizes the use of single path routing, and uses multipath when no single path can be found to accommodate the requested bandwidth. The proposed algorithm is compared to four other algorithms that use single path routing. Results indicate that 100% protection for single failures with low overhead can be provided by the proposed algorithm.**

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

I. Introduction

The rapidly approaching of the exhaustion of the capacity of single-core optical fibers in the face of growing demands for bandwidth has led to the introduction of spatial division multiplexing (SDM) in elastic optical networks for increasing the network capacity. SDM involves using spatial channels and can be realized by using multi-core fiber (MCF). In SDM employing MCF, each core acts as a single mode fiber increasing the network transmission capacity. For spatial division multiplexing elastic optical networks (EONs), the RSA problem becoming the routing, spectrum and core allocation (RSCA) problem.

In SDM EONs the establishment and tear down of lightpaths leads to the fragmentation of the spectrum which is a state in which there are available slots, but not gathered in a way that can be used to accept new requests. This problem is called fragmentation problem; the segmentation of the available spectrum into small non-contiguous bands. The use of multipath routing offers the advantage of using small contiguous bands in multiple paths for the request, increasing the number of accepted requests.

In elastic optical networks, multipath routing is used to increase the utilization of network resources. In addition, this type of routing increases the reliability of data delivery. Multipath routing is used to increase the utilization of network resources. In addition, this type of routing increases the reliability of delivery. Multipath routing aims at efficiently exploiting network resources by using multiple paths between source-destination pairs. The use of multipath routing in SDM EONs can lead to higher spectrum usage, less blocking [1], [2], and increased survivability [1], [2]. We call hybrid routing policies those which first try to allocate single paths for a request and if not possible allocate multiple paths for the request.

P-cycle is a protection scheme in which the spare capacity is pre-connected to form ring-like structures called p- cycle [3]. The main difference to conventional ring protection is that p-cycles provide two protection paths for each link that straddles the cycle. The straddling links can have working capacity but no spare capacity [3]. A special case of p-cycle for path protection is the so called Protection to Failure-Independent Path Protecting (FIPP) [4]. FIPP p-cycles not only protect end-to-end working paths on the p-cycle, but also those with end node on their cycle. FIPP is an extension of the p-cycle concept. Failures are not limited to a link or path segment immediately adjacent to the end nodes. This restriction leads to failure independence, which implies that fault detection is independent of the location where a fault has occurred. This allows faults to be detected in real time by end nodes which is a great advantage for transparent and translucent networks in which fault location is slow and complex. Indeed, FIPP p-cycle is based on Shared-Backup Path Protection (SBPP) which is a preplanned path restoration scheme defined for the Internet Protocol (IP) networks.

Despite the increase in capacity, the SDM EONs remain susceptible to failures, since failure is quite frequent in operational optical networks. It is estimated that there is a failure every four hours in operational networks. Several studies on protection in optical networks have been carried out [5]–[8], but, only recently, the study of spatial division multiplexing for protection in elastic optical networks has been considered [9]–[11]. In this context, although routing, spectrum, and core allocation algorithms have been proposed in the literature, only few papers consider protection. In addition, Failure-Independent Path Protecting (FIPP) p-cycle and multipath routing have not been considered simultaneously.

In this paper, we propose a routing, spectrum and core allocation (RSCA) problem algorithm entitled the P-cycle path pRotection and hybrId routing for Multicore nEtwork (PRIME) for providing 100% protection against single failure for elastic optical networks with space division multiplexing.

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The PRIME algorithm chooses the shortest paths as primary paths. If not possible to allocate the request in a single path, multipath is employed for the primary path. In both cases, the backup path is an FIPP p-cycle which can be shared but the same p-cycle can not protect more than one path belonging to the same connection. Moreover, we show that multiple routing contributes to slicing the network bandwidth, allowing the support of data transfer rates greater than what is possible on a single path.

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

II. Related Work

To the best of our knowledge, this is the first attempt to consider hybrid routing and protection in spatial division multiplexing in elastic optical networks.

In [12], it was introduced an RCSA algorithm based on the connected component labeling (CCL) algorithm. Spectrum fitting policies are also proposed to be jointly employed with the CCL algorithm. However, protection is not considered.

Hirota *et.al.* [13] divide the RSCA problem into the routing, and core and spectrum assignment (SCA) problems, and introduces a K-shortest path based pre-computation method as the routing solution. They proposed SCA methods with crosstalk awareness. However, protection is not considered.

Tan *et.al.* [9] investigate about dedicated path protection with considering inter-core crosstalk in SDM EONs. The authors use K-shortest-path (KSP) algorithm to obtain a primary path and backup path. After they solve the problem of inter-core crosstalk between adjacent cores, but share protection is not used.

In [14], the authors investigated the benefits of multipath routing in an environment which includes inter-domain routing issues in WDM optical networks.

Chen *et.al.* [15] proposed a multipath routing in WDM optical networks for emerging high-performance applications with extremely high bandwidth requirements.

In [16], multipath routing was applied to serve connection requests with known duration. The authors formulated an optimization model based on Integer Linear Programing (ILP) to leverage multipath routing and grooming in WDM optical networks.

In [17], some approaches routing using traffic grooming and multipath in WDM optical networks were studied.

In [18], the potential gains by jointly employing traffic grooming and multipath routing is investigated with a realistic physical impairment model for elastic optical networks.

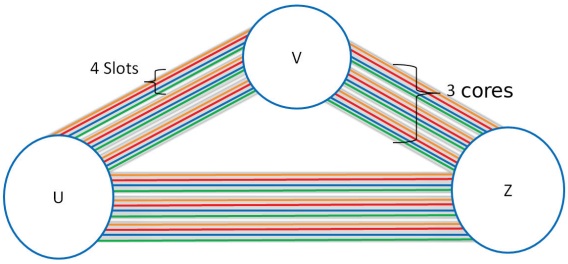
Ruan *et.al.* [2] study the survivable and multipath problem in elastic optical network. The solution proposed selects multiple routes and allocates spectrum on these routes for a given demand as it arrives at the network. The papers [18] and [2] do not considered spatial division multiplexing.

III. The Algorithm

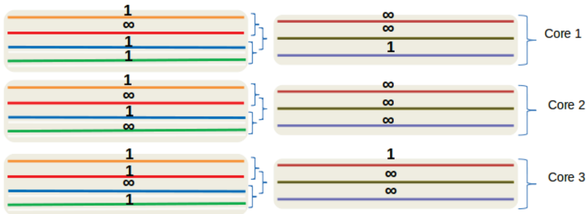
This section introduces P-cycle path pRotection and hybrId routing for Multicore nEtwork (PRIME) algorithm. In this algorithm, a connection can use either single path or multipath. In both cases, the lightpaths are protected by a p-cycle. Multipath is employed in the establishment of a connection in case it is not possible to establish only a single path for the connection. When a simple path is employed as primary path, an FIPP *p-cycle* is used as the backup path. When multipath are employed, for each primary path, a FIPP *p-cycle* is established for protection. Although p-cycles can be shared, under no circumstances the same *p-cycle* can protect more than one path of the same connection. The PRIME algorithm assures a protection path for each established lightpath against single failures.

Unlike other algorithms [9], [12], [13] that first find the path and then the slots and cores to be used, this algorithm performs the path search considering the slots and core availability along the path. For this, we model the spectrum availability in the network as labeled multigraph [19]. In the multigraphs, each edge represents a slot of the core (Fig. 1a). In these multigraphs, an ∞ label value in an edge means that a slot is already allocated whereas a value greater than zero means that the slot is available for allocation. To assure the spectrum contiguity constraint to the solution, we mapped $N - b + 1$ edges in one edge in a new multigraph, where N is the number of slots in a core and b is the number of slots necessary to satisfy the request. Then each edges in these new multigraphs represent a combination of b slots. In these edges, an ∞ label value means that at least one slots is already allocated whereas the value greater than zero means that all slots are available for allocation (Fig. 1b). In the new multigraphs, an edge represents b continuous slots and each multigraph represents a core. Since only one core and the same edge set in all links can be used in a path, we divide each edge of the multigraph into a set of graphs (Fig. 1c).

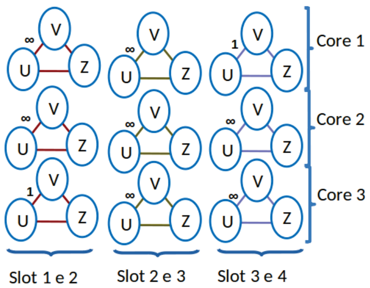
In the PRIME algorithm (algorithm 1), Line 1 transforms the multigraph into graphs as described before. Line 2 solves a shortest path algorithm for the graphs. To compute the shortest path the Dijkstra algorithm is executed on all graphs. If it is possible to find a path under the contiguity constraint for the demand b, then a p-cycle to protect the lightpath to be established is searched (Line 3). In case a path and a protecting p-cycle exist, the lightpath is established (Line 5). Otherwise, a p-cycle to protect the lightpath to be established needs to be created (Lines 7). To compute the p-cycle the Suurballe algorithm [20] is executed on all graphs for selecting the shortest p-cycle. In case the p-cycle can be created to protect a lightpath, the lightpath as well as the p-cycle (Lines 9) are established to satisfy the request. Otherwise, a multipath is used (Line 14 to 33). Line 14 transforms the multigraph in graphs considering the division of the bandwidth into k paths. Line 15 solves a k-shortest path algorithm for the graphs and finds k-paths. To compute the k paths, the Dijkstra algorithm is executed on all graphs, and selecting the k-shortest path. If



(a) Network with 3 cores and 4 slots.



(b) Set edges are mapped in to one edge, contiguity constraint.



(c) Set edges in multigraph are mapped in graphs

Figure 1: Transforming multigraph in graphs

Algorithm 1 PRIME

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

it is not possible to find k paths under the contiguity constraint for the demand b (line 16), then the request is blocked (line 17). Otherwise, a p-cycle to protect each path to be established is searched (Line 19). If there is no p-cycle to protect the k path, a p-cycle to protect the path to be established is created (Line 21). In case it is not possible to create the p-cycle, the request is blocked. If all p-cycles can be created, the lightpath as well as the p-cycle (Lines 28) are established to satisfy the request.

The complexity of the PRIME algorithm is analyzed as follows. The complexity of transforming the original multigraph in graphs is $O(E+V)$. Dijkstra complexity is $O(E+VlogV)$. Suurballe's complexity is $O(E+VlogV)$. The complexity of the PRIME algorithm is then $O(E+VlogV)$.

IV. Performance Evaluation

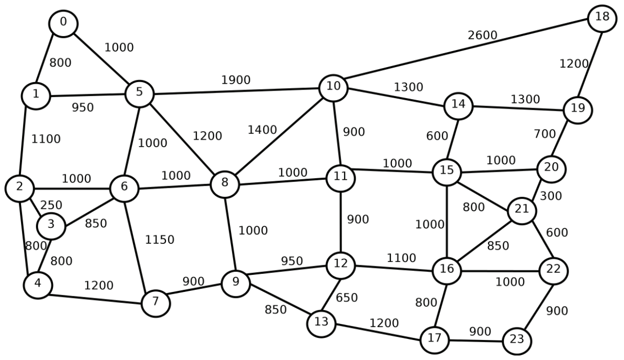
To assess the performance of the proposed algorithm in multi-core networks, simulation experiments were conducted employing the FlexGridSim [21]. The network load was varied from 25 to 500 erlangs, and each simulation involved 100,000 connection requests. Seven types of requests were employed 25 Gbps, 50 Gbps, 125 Gbps, 200 Gbps, 500 Gbps, 750 Gbps and 1 Tbps. The links were composed by MCFs with 7 core and each core was divided into 320 slots. 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.

The topology used in the simulations were the USA (Figure 2a) and the NSF (Figure 2b) topologies. The NSF topology has 14 nodes and 20 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. The modulation format BPSK was used with 1 bit per symbol. In this paper, BPSK modulation format is employed for extensions of 4000 km with slot capacities of 12.5 Gb/s.

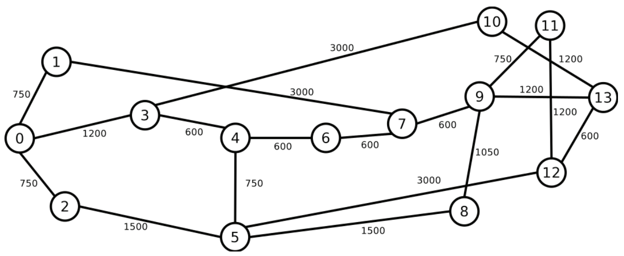
To calculate the crosstalk (XT) from one core in relation to n neighboring cores, in a homogeneous MCF fiber, we used (2). Considering the coupled-power theory [22] [23], and using (1) leads to (2), which was used to ensure the quality of transmission of the connections.

$$h = \frac{2 \cdot k^2 \cdot R}{\beta \cdot D} \tag{1}$$

Eq. 1 expresses the mean crosstalk increase per unit length;



(a) USA Topology



(b) NSF Topology

Figure 2: Topologies

h is the mean crosstalk increase per unit length, k, β, R, D are coupling coefficient, propagation constant, bend radius and core-pitch, respectively.

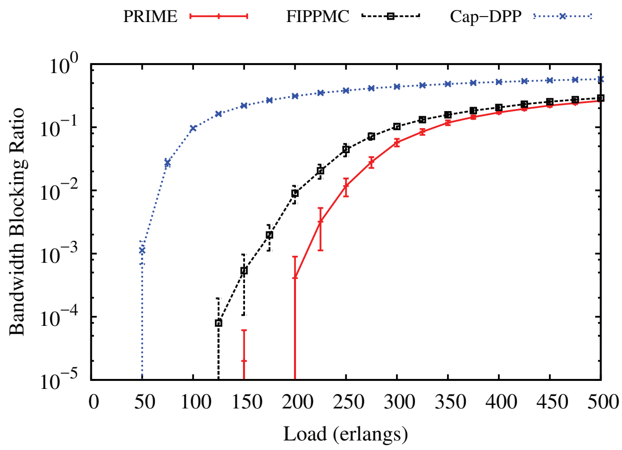
$$XT = \frac{n\{1 - exp(-(n+1) \cdot 2 \cdot h \cdot L\}}{1 + n\{exp(-(n+1) \cdot 2 \cdot h \cdot L)\}} \quad (2)$$

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

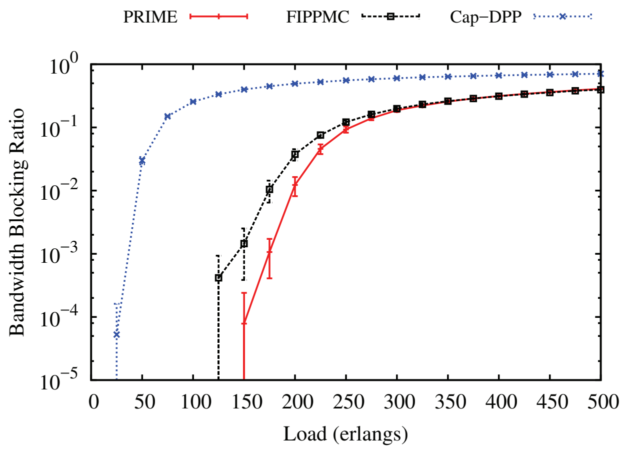
Results are compared to those derived by the CaP-DPP [9] and FIPPMC [19] algorithms. The CaP-DPP uses a crosstalk-aware provisioning strategy with dedicated path protection whereas FIPPMC algorithm uses a FIPP p-cycle for provide protection. None of these algorithms employ hybrid routing.

Fig. 3 shows the bandwidth blocking ratio (BBR) as a function of the load for the USA and the NSF topologies. Bandwidth blocking ratio is defined as the amount of bandwidth blocked over the amount of bandwidth requested.

For the USA topology (Fig. 3a), while Cap-DPP and FIPPMC start blocking requests under loads of 50 and 125 erlangs, respectively, the PRIME algorithm starts blocking only under loads of 150 erlangs. Under loads of 200 erlangs, the difference between the BBR produced by the PRIME algorithm and those algorithm produced by the FIPPMC and Cap-DPP are one and almost three order of magnitude, respectively. The low BBR values produced by the PRIME algorithm evince the benefits of considering multipath when it is not possible to use a single path only. The high BBR values produced by Cap-DPP is a consequence of the lack of sharing of backup paths. Besides that, such trend is a consequence of the FIPPMC and the PRIME algorithms employing FIPP p-cycle and the multigraph representation of the spectrum. These results show that the PRIME algorithm produces acceptable blocking for SDM-EON despite the bandwidth reservation for pre-provisioning of backup paths.



(a) USA Topology

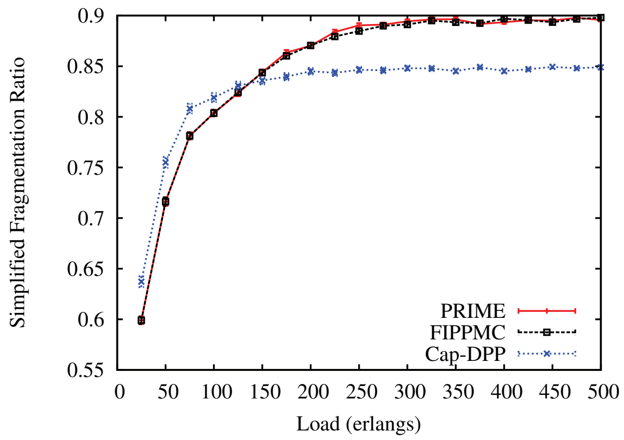


(b) NSF Topology

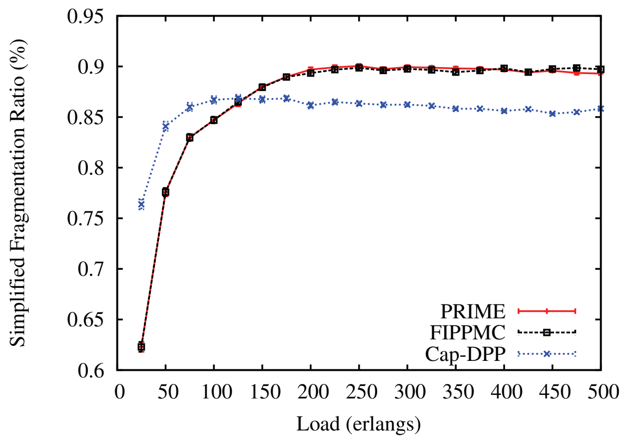
Figure 3: Bandwidth blocking ratio

For the NSF topology (Fig. 3b), results are similar to those obtained for the USA topology. While Cap-DPP and FIPPMC start blocking requests under loads of 25 and 125 erlangs, respectively, the PRIME algorithm starts blocking only under loads of 150 erlangs. For loads of 175 erlangs, the difference between the BBR produced by the PRIME algorithm and that given by the FIPPMC and Cap-DPP algorithms is two and one order of magnitude, respectively. Under loads of 250 erlangs, the BBR values produced by the PRIME algorithm is similar to the values produced by the FIPPMC algorithm.

Fig. 4 shows the fragmentation ratio as a function of the load for the USA and NSF topologies. In elastic optical networks, the establishment and tear down of lightpaths leads to the fragmentation of the spectrum which is a state in which there



(a) USA Topology



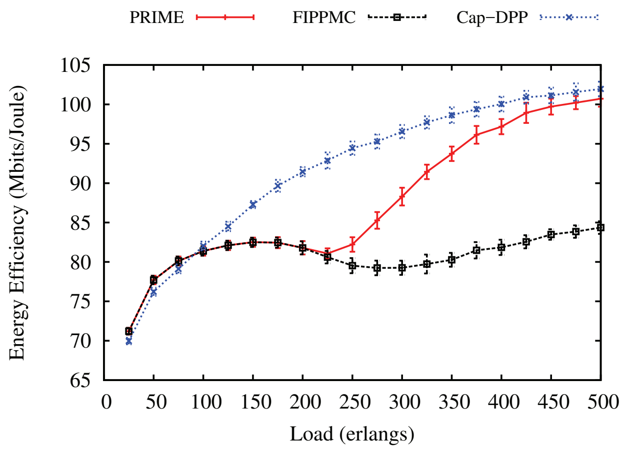
(b) NSF Topology

Figure 4: Fragmentation ratio

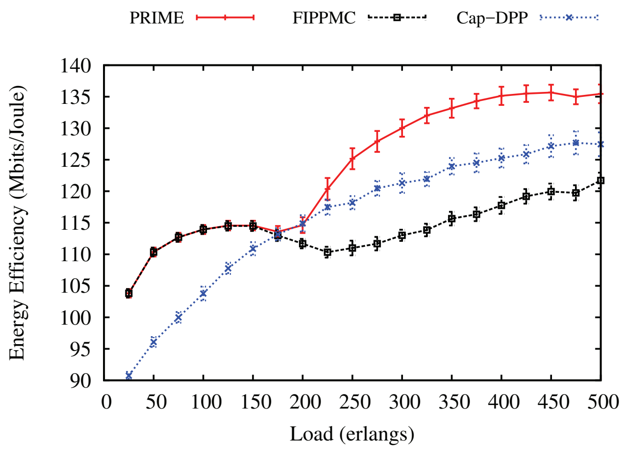
are available slots that cannot be gathered in a way to be used to accept new requests.

The fragmentation ratio as a function of the traffic load for the USA topology is shown in Fig. 4a. Under low loads the fragmentation ratios produced by the Cap-DPP algorithm are the highest ones. This is a consequence of not sharing backup paths, which generates a lower number of disconnected backup paths, and reduces the number of available spectrum that can not be allocated by the incoming requests. For loads greater than 125 erlangs, the PRIME and FIPPMC algorithms produce fragmentation ratio 5% higher than that produced by the Cap-DPP algorithm. This is a consequence of the blocking due to the low number of alternative paths. For the FIPPMC and PRIME algorithms, the difference in fragmentation ratio exists only for loads greater than 200 erlangs. The utilization of multipath in the PRIME algorithm evinces the advantage of such a combination in contrast to the blocking of the other algorithms.

For the NSF topology (Fig. 4b), results are similar to those obtained for the USA topology. Under low loads of 25 erlangs the Cap-DPP algorithm produces the highest fragmentation ratios. This algorithm produces a fragmentation ratio 12% greater than the PRIME and FIPPMC algorithms which use p-cycles for providing protection. Under load greater than 150 erlangs, the CaP-DPP algorithm produces the lowest fragmentation ratio which is a consequence of the smaller number of requests accepted and the shortest paths used. For the FIPPMC and PRIME algorithms, the difference between the fragmentation ratios exists only for loads greater than 150 erlangs. This happens because only under these loads there is the need for multipath routing.



(a) USA Topology



(b) NSF Topology

Figure 5: Energy efficiency

Fig. 5 shows the energy efficiency as a function of the load for the USA and NSF topologies. The energy efficiency is obtained by dividing the total traffic demand successfully served in the network by the total energy consumption.

The energy efficiency associated with these algorithms for the USA topology is shown Fig. 5a. Under high loads, the Cap-DPP algorithm leads to the greatest energy efficiency of all the algorithms tested, as a consequence of producing high BBR values and employing only short paths. Up to loads of

225 erlangs, there is not much difference between the energy efficiency produced by the FIPPMC and that produced by the PRIME algorithm. Difference in energy efficiency arise only under higher loads, as a consequence of the PRIME algorithm allocating multiple paths for request when the allocation of a single path is not possible. The use of multiple paths allows the allocation of shortest paths since the allocated paths use a lower number of continuous slots. The allocation of smaller paths increases the energy efficiency.

Fig. 5a illustrates the energy efficiency resulting from the use of algorithms for the NSF topology. Until loads of 175 erlangs, the Cap-DPP algorithm leads to the lowest energy efficiency in despite of producing the highest BBR. Under loads higher than 175 erlangs, the PRIME algorithm leads to the highest energy efficiency as well as the lowest BBR values, since the use of multipath decreased the number of hops in the allocated paths. Differently than the results for the USA topology, under high loads, the energy efficiency produced by the PRIME algorithm is higher than that produced by the other algorithms.

V. Conclusion

In this paper we proposed a novel approach to support the establishment of lightpaths in elastic optical networks with spacial division multiplexing protected by FIPP p-cycle and hybrid routing. The use of hybrid routing reduced the blocking of requests since allocating multiple paths for the request facilitated the ensurance of the continuity and contiguity constraints. The PRIME algorithm was evaluated for different topologies and loads and compared to other algorithms that employ single path routing. Simulation results evinces the lower blocking produced by the PRIME algorithm when compared to the other evaluated algorithms which evinces the advantage of employ hybrid routing for EON-SDM.

Acknowledgments

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