Differentiated Resource Allocation in Resilient SDM-EON

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***Abstract*—Resilience is a critical issue to the Space-Division Multiplexing Elastic Optical Networks technology due to the enormous amount of data these networks carry. This paper proposes a routing, modulation, spectrum, and core allocation algorithm supporting differentiated resilience services. The proposed mechanism uses classes of service to provide transport services to requests for lightpath establishment. It reduces wastage of spectrum in the provisioning of protected services and proposes a spectrum release mechanism. The results obtained demonstrate the high efficiency of the proposed algorithm in the provisioning of resilience to high priority requests compared to similar algorithms in the literature, reaching a lower blocking probability of up to 60%.**

***Index Terms*—Optical Networks, Space Division Multiplexing, Routing, Resilience, DiffServ**

I. INTRODUCTION

Recent research demonstrates the effectiveness of adding Space-Division Multiplexing (SDM) to enlarge Elastic Optical Networks (EON) [1]. Broadening existing solutions to the Routing, Modulation, and Spectrum Allocation (RMSA) problem calls for optimal allocation of the spectrum in EON. In such solutions, must obey the continuity and contiguity restrictions. The continuity constraint imposes the need for the spectrum band to be the same on all links of the chosen route, avoiding optoelectrical signal conversion at the network nodes. The contiguity restriction imposes that the frequency slots allocated be contiguous. Moreover, the possibility of employing different modulation levels allows high data transmission rates using fewer slots and large numbers of bits per symbol transmitted [2]. With the addition of the spatial dimension, it is possible to allocate spectrum in multiple cores, consequently increasing the complexity of the RMSA, which becomes the Routing, Modulation, Spectrum, and Core Allocation (RMSCA) problem.

Solutions to the RMSCA problem, including resilience provisioning, are of paramount importance to SDM-EON since the massive loss of data happens if a link failure occurs, given the high transmission rates in these networks. There are two central resilience schemes in the literature: protection and restoration. Protection schemes offer greater security and immediate connection recovery in the event of failure. However, the drawback is the additional resources required, which leads to the fast exhausting of the available resources, increasing the blocking of requests for lightpath establishment. On the other hand, restoration schemes offer greater spectral efficiency, given its reactive approach of seeking a new path for connections only when a failure occurs, at the cost of significant delays in the recovery of the failed connection. Moreover, there is no guarantee of success in recovery attempts since the required resources may be unavailable at the time of failure. Therefore, there is a need to develop new mechanisms that low overhead and ensure efficient recovery against failures.

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Other relevant aspects include traffic heterogeneity and imply in Quality of Service (QoS) requirements. For example, services of online games and telemedicine, which had significant growth during the social isolation period due to the pandemic of COVID-19 [3], require large bandwidth and low latency [4]. Still, their reliability resilience requirements (Quality of Protection - QoP) significantly differ [5]. Telemedicine connections have strict requirements, while online game services do not have such requirements [6]. Thus, there is a clear need to implement mechanisms that consider the main requirements of each connection for the efficient provisioning of resources.

In this paper, we propose an RMSCA algorithm for SDM-EON, which includes a protection mechanism to provide different levels of QoP, called INCREASER-QoP. The proposed algorithm can provide the required resources for different requests. The INCREASER-QoP algorithm uses a combination of Dedicated Path Protection (DPP) and Shared Backup Path Protection (SBPP) strategies for resource allocation. Furthermore, with preemption, which allows the removal of resources from low-priority flows to provide them to high-priority flows, the INCREASER-QoP algorithm can capitalize on the advantages of both protection and restoration mechanisms, with the guaranteed recovery connections and greater spectral efficiency.

We organize the remainder of the paper as follows. Section II outlines the state-of-the-art space-division multiplexing EON. Section III describes the INCREASER-QoP algorithm. Section IV discusses the simulation description and results. Finally, Section V introduces the conclusions.

II. RELATED WORKS

Few studies on SDM-EON have dealt with differentiated resource allocation for network resilience. Our best knowledge is that this is the first paper that considers shared path protection based on the preemption policy in SDM-EON.

Hai [7] introduced the concept of protection with QoS recognition, making it possible to separate flows into best-effort traffic and premium traffic. This strategy gives guarantees only to premium traffic, allowing quick recovery of this type of connection. However, the authors do not consider SDM-EON and do not use a spectrum release policy to benefit lightpath with high priority. Oliveira and da Fonseca [2] propose an algorithm to dynamically generate primary and backup paths using a shared backup scheme. However, the authors do not consider Classes of Service (CoS) and use a spectrum release policy.

Santos *et al.* [8] present a model for dealing with overload in elastic optical networks, using service degradation and proportional QoS. The authors considered differentiation based on parameters assigned by network operators. However, the proposed algorithm neither considers the protection of flows, which are discarded in case of failures nor considers SDM-EON. Tan *et al.* [9] investigated dedicated path protection taking into account inter-core crosstalk in SDM-EONs. The authors used the K-shortest-path (KSP) algorithm to obtain primary and backup paths but did not consider path share protection and CoS priority.

Vyas [10] proposes four resource provisioning heuristics in EON, employing a combination of resource allocation and bandwidth division. It shows the advantages of using bandwidth division compared to preemption. However, it does not consider SDM networks. Zhu *et al.* [11] proposed a routing, modulation, and core and spectrum allocation (RMSCA) algorithm with floating traffic in SDM-EONs. The authors investigated the efficiency of resource allocation by minimizing the impact of crosstalk on the probability of blocking. However, the proposed algorithm does not consider QoP, ignoring different priorities for requests.

III. INCREASER-QOP ALGORITHM

This section presents an RMSCA algorithm for the traffic prioritization in SDM-EON, which considers QoP to optimize the allocation of resources for path protection and maintain a low overhead.

Based on a differentiated resource provisioning policy, we introduce the Rout**IN**g Modulation Spe**C**t**R**um and Cor**E** **A**llocation U**S**ing Diff**ER**entiation by **QoP** (INCREASER-QoP) algorithm. Different classes have different protection guarantees. Resource allocation is optimized by considering protection for only a portion of the traffic, which results in more significant spectral savings.

INCREASER-QoP classifies the traffic into three Classes of Service (CoSs) requiring differentiated QoP. The aim is to prioritize the acceptance of requests with high priority, providing them with minimum recovery time in case of failure along their route. Table I shows the characteristics of each CoS. CoS 1 requests are the ones that have the greatest QoP. They use dedicated path protection and preemption on primary and backup paths when needed. CoS 2 requests have intermediate QoP. They use shared path protection and preemption on primary and backup paths when needed. CoS 3 requests have the lowest priority and consequently unprotected traffic.

TABLE I
CLASS OF SERVICE CHARACTERISTICS.

CoS	Preemption	QoP	Protection
1	✓	High	Dedicated
2	✓	Medium	Shared
3		Low	Not Required

The INCREASER-QoP algorithm employs a preemption technique, allowing low priority lightpaths to be released when needed for higher priority requests. This characteristic can lead to larger request acceptance ratios and greater energy efficiency.

A. INCREASER-QoP Notation

The following mathematical notation will be used:

- s: the source node of the request r;
- d: the destination node of the request r;
- q: the class of service of the request r;
- b: the demand for bandwidth, plus guard band of the the request r;
- $r(s, d, q, b)$: the request from node s to node d, with CoS q and demand b;
- $G(N, E)$: the network graph, where N is the set of nodes and E is the set of links on the network;
- $\widetilde{G}(\widetilde{N}, \widetilde{E})$: an auxiliary network graph, formed by the set of nodes $\widetilde{N}$, and the set of links $\widetilde{E}$;
- $\Upsilon(G, s, d)$: the set of routes (only links) between nodes s and d, in the graph G;
- υ_i: the ith route in the Υ set;
- $\mu(\upsilon)$: the best modulation level for the υ route;
- $\mu(\delta)$: the best modulation level for the route of the lightpath δ;
- $\Omega(\upsilon, \mu, b)$: searches for a free lightpath between nodes s and d, which passes through the node-set υ, with the modulation level μ and which supports demand b;
- $\omega_{s,d,b}$: a free lightpath between nodes s and d, which supports demand b;
- $\Delta(G, q)$: The set of all active lightpaths in G, which were allocated by requests which CoS priorities greater than q;
- δ_i: the ith active lightpath in G;
- $\Phi(\delta, \mu(\delta_{s,d})\ s, d, b)$: checks if the route of the active lightpath δ or any sub-route $\delta_{s,d}$ in the route of the δ connects nodes s and d, and if under the best modulation $\mu(\delta_{s,d})$, for the route between s and d, the $\delta_{s,d}$ supports b demand;
- $\phi_{s,d,\mu(\delta),b}$: released lightpath between nodes s and d, using modulation $\mu(\delta)$ and which supports demand b;
- η: number of slots, continuous and contiguous, that meet demand b;
- α: the primary lightpath of the request r;
- β: the backup lightpath of the request r;
- $\widehat{\Delta}(G, q)$: the set of all backup lightpaths in G allocated by requests CoS q;
- $\widehat{\delta}_i$: the ith allocated backup lightpath in the $\widehat{\Delta}$ set;
- $\Gamma(\widehat{\delta}, s, d, \mu(\widehat{\delta}))$: checks if the route of the active lightpath $\widehat{\delta}$ or any sub-route $\widehat{\delta}_{s,d}$ in the route of the $\widehat{\delta}$ connects nodes s and d, if under the best modulation $\mu(\widehat{\delta}_{s,d})$, for the route between s and d, the $\widehat{\delta}_{s,d}$ supports b demand, and if α is disjoint to the primary path of the request that allocated the $\widehat{\delta}$;

- γ_i: a lightpath available to be dedicated backup path;
- $\widehat{\gamma}_i$: a lightpath available for sharing to the backup path;

B. INCREASER-QoP Operations

In the INCREASER-QoP (Algorithm 1), Line 1 computes *k* shortest paths between the source and destination nodes of the request. For this, we execute the YEN [12]. Moreover, for each route, INCREASER-QoP checks whether there are η free slots, given the best modulation level for this route (Line 2). If there is an $\omega_{s,d,\mu(\upsilon),b}$, INCREASER-QoP allocates this as the primary lightpath of *r* (Line 3). Otherwise, if an $\omega_{s,d,\mu(\upsilon),b}$ that meets the imposed restrictions is not found (Line 4), a search is done for a lightpath allocated by a request of CoS greater than *q* that supports demand *b*, among all the active lightpaths in the network (Line 5). Then, the best modulation level for the sub-route between *s* and *d* is selected and checked if there are η allocated slots in its lightpath. If there is a $\phi_{s,d,\mu(\delta),b}$ with η or less allocated slots (Line 6), INCREASER-QoP allocates this $\phi_{s,d,\mu(\delta),b}$ as the primary lightpath of *r* (Line 7). For this, the flow that had allocated the lightpath containing δ is interrupted. Otherwise, the request *r* is blocked.

If the allocation of the primary lightpath is successful, INCREASER-QoP assesses the need for a backup lightpath for the request. Therefore, in Line 12, it is verified if the request's CoS is less than 3. If not (Line 45), the request is accepted without searching for a backup lightpath (Line 46). Otherwise, INCREASER-QoP checks the type of backup path to be established. If the request is for CoS 2 (Line 13), INCREASER-QoP search a shared backup path. For this, INCREASER-QoP creates an auxiliary graph that does not contain the primary lightpath allocated to *r* (Line 14), ensuring that the allocated β are disjoint to α. Then, all backup lightpath active in the network $\widetilde{G}$ and allocated by CoS 2 requests are analyzed to verify if it contains any route that connects nodes *s* and *d* (Line 15). In addition, INCREASER-QoP verifies if under the best modulation level for the route between *s* and *d*, lightpath $\widehat{\delta}$ meets the demand requirements *b*.

If there is a $\widehat{\gamma}_{s,d,\mu(\widehat{\delta}),b}$ lightpath in Γ that has η allocated slots (Line 16)), INCREASER-QoP share this as a protection lightpath for *r* (Line 17). Otherwise, INCREASER-QoP searches for an active lightpath, allocated by lower priority requests, with η slots allocated (given the best level of modulation for the route between *s* and *d*) and a sub-route between nodes *s* and *d* (Line 19). If it is found (Line 20), then the lightpath $\phi_{s,d,\mu(\phi),b}$ with a route between *s* and *d* is preemptively allocated to the request *r* (Line 21). Preemptive allocation to the backup lightpath does not require interrupting the flow allocated to the lightpath preempted. In addition, for this case, the preemptively allocated lightpath is available for sharing as a backup path to other CoS 2 requests. If INCREASER-QoP cannot find a preemptive backup path for the *r* request for CoS 2 (Line 22), this searches for free η slots for each of the *k* shortest routes between *s* and *d*, disjoint to the α route (Line 23). If there is an $\omega_{s,d,\mu(\upsilon),b}$, then it is allocated as β of *r*. If a protection lightpath is still not found for the request *r*, then it is blocked.

Algorithm 1: INCREASER-QoP

```
   Input: $r(s, d, q, b)$, $G(N, E)$
   Output: Request Status
1  $\Omega(\upsilon_i, \mu(\upsilon_i), b) \forall \upsilon_i \in \Upsilon(G, s, d)$;
2  if $\exists \omega_{s,d,\mu(\upsilon),b}$ then
3      $\alpha \leftarrow \omega_{s,d,\mu(\upsilon),b}$;
4  else
5      $\Phi(\delta_i, \mu(\delta_{i,s,d}), s, d, b) \forall \upsilon_i \in \Delta(G, q)$;
6      if $\exists \phi_{s,d,\mu(\delta),b}$ then
7          $\alpha \leftarrow \phi_{s,d,\mu(\delta),b}$;
8      else
9          Blocks request r;
10     end
11 end
12 if $q < 3$ then
13     if $q = 2$ then
14         $\widetilde{G}(\widetilde{N}, \widetilde{E}) \leftarrow G(N, E) - \alpha$;
15         $\Gamma(\widehat{\delta}_i, s, d, b, \mu(\widehat{\delta}_{i,s,d})) \forall \widehat{\delta}_i \in \widehat{\Delta}(\widetilde{G}, q)$;
16         if $\exists \widehat{\gamma}_{s,d,\mu(\widehat{\delta}),b}$ then
17             $\beta \leftarrow \widehat{\gamma}_{s,d,\mu(\widehat{\delta}),b}$;
18         else
19             $\Phi(\delta_i, \mu(\delta_{i,s,d}), s, d, b) \forall \delta_i \in \Delta(\widetilde{G}, q)$;
20             if $\exists \phi_{s,d,\mu(\delta),b}$ then
21                 $\beta \leftarrow \phi_{s,d,\mu(\delta),b}$;
22             else
23                 $\Omega(\upsilon_i, \mu(\upsilon_i), b) \forall \upsilon_i \in \Upsilon(G, s, d)$;
24                 if $\exists \omega_{s,d,\mu(\upsilon),b}$ then
25                     $\beta \leftarrow \omega_{s,d,\mu(\upsilon),b}$;
26                 else
27                     Blocks request r;
28                 end
29             end
30         end
31     else if $q = 1$ then
32         $\Omega(\upsilon_i, \mu(\upsilon_i), b) \forall \upsilon_i \in \Upsilon(\widetilde{G}, s, d)$;
33         if $\exists \omega_{s,d,\mu(\upsilon),b}$ then
34             $\beta \leftarrow \omega_{s,d,\mu(\upsilon),b}$;
35         else
36             $\Gamma(\delta_i, s, d, b, \mu(\delta_{i,s,d})) \forall \delta_i \in \Delta(\widetilde{G}, q)$;
37             if $\exists \gamma_{s,d,\mu(\delta),b}$ then
38                 $\beta \leftarrow \gamma_{s,d,\mu(\delta),b}$;
39             else
40                 Blocks request r;
41             end
42         end
43     end
44     Accept r with $\alpha$ and $\beta$;
45 else
46     Accept r with $\alpha$;
47 end
```

If the request *r* is for CoS 1 (Line 31), then INCREASER-QoP searches for a dedicated protection lightpath, checking the availability of η slots in each *k* shortest route (Line 32). If the algorithm finds an $\omega_{s,d,\mu(\upsilon),b}$ (Line 33), it allocates the $\omega_{s,d,\mu(\upsilon),b}$ as a backup lightpath of *r* (Line 34). If INCREASER-QoP does not find an $\omega_{s,d,\mu(\upsilon),b}$ (Line 35), a search is made for a preemptive backup path between nodes *s* and *d*, checking all active lightpaths on the network and allocating for CoS requests greater than *q* (Line 36). If INCREASER-QoP finds a lightpath that meets these conditions (Line 37), allocate it as a backup lightpath for r (Line 38). In this case, different from what happens with preemptive backup paths for CoS 2 requests, the backup lightpaths allocated by CoS 1 requests cannot be shared. If the algorithm does not find a $\gamma_{s,d,\mu(\delta),b}$ (Line 39), the request r is blocked (Line 40). Finally, if INCREASER-QoP can to allocate both a primary and a backup path (for CoS requests less than 3), the request r is accepted.

IV. PERFORMANCE EVALUATION

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

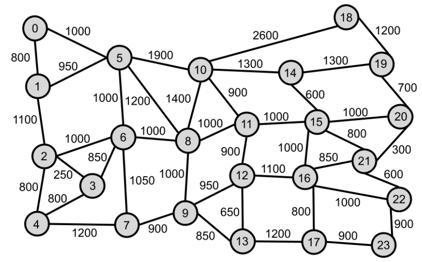
A. Network Setting

In this paper, the network considered has bidirectional fiber-optic links, with seven cores arranged in a hexagonal shape. Cores have an available spectrum of 4 *THz*, divided into 320 slots of 12.5 *GHz*. The length of the links is taken from real topologies. Various modulation levels are employed, aiming at increasing the data transfer rates using fewer allocated slots. Due to limitations in the signal decoding, the choice of the modulation level for each request is based on the length of the route. It can be the 64QAM, 32QAM, 16QAM, 8QAM, QPSK, and BPSK modulation formats for distances 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 [13]. We considers the use of add/drop multiplexers, which allows the addition, blocking, removal, and switching of optical signals, adaptable to the bandwidth required by each request. Moreover, we considers a transparent optical network to reduce the cost of conversions at intermediate nodes.

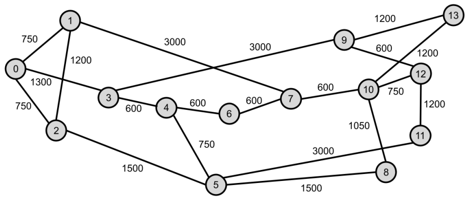
B. Scenario description and methodology

We used the FlexGridSim discrete event simulator [14], with additional modules that allowed the simulation of an SDM-EON, and traffic differentiation. We used topologies of real scenarios: the USA (Figure 1(a)), which contains 24 nodes and 43 links, and the NSF (Figure 1(b)), which contains 14 nodes and 25 links. We performed a total of 20 simulations, with load varying in 50 erlangs between loads of 50 and 1000 erlangs. In each simulation, 100,000 requests were processed, which in bandwidth request varied between 25/50/125/200/500/750/1000 Gbps. Traffic was generated randomly using a Poisson process, and classes of service according to the Table I. In this work, we consider heterogeneous traffic with only 25% of traffic having high protection requirements (where 16.7% are CoS 2 requests and 8.3% are CoS 1 requests), according to current traffic trends [7], [15].

The metrics used for the performance evaluation are Bandwidth Blocking Ratio (BBR), which is equivalent to the ratio between the sum of all bandwidth blocked, and the total bandwidth requested; the CoS Blocking Ratio by CoS, which is the ratio between the sum of the entire blocked bandwidth for requests for CoS, and the total bandwidth requested; Energy Efficiency, which is equal to the ratio between the amount of data carried by the network (in Mbits) and the energy consumption of the network (in Joules).



(a) Topologia USA



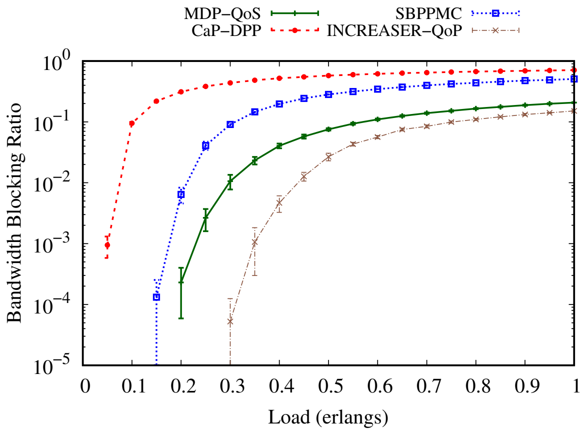
(b) Topologia NSF

Fig. 1. Topologias

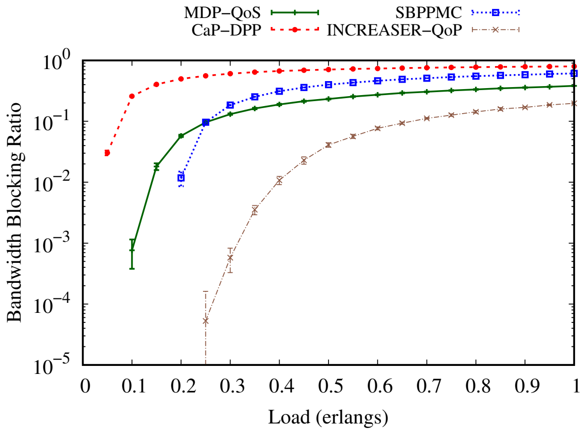
C. Results

In the figures, the curves labeled “INCREASER-QoP” show the INCREASER-QoP algorithm’s performance. The curves labeled “MDP-QoS” shows the results obtained in the simulations of the MDP-QoS algorithm proposed in [16]. The curves with the label “CaP-DPP” show the CaP-DPP algorithm’s performance proposed in [17]. The curves labeled “SBPPMC” show the performance of the SBPPMC algorithm proposed in [2]. Due to the lack of algorithms that consider the differentiation of services and operate in SDM, trying to be as fair as possible, we chose three algorithms with similar characteristics but operated initially in EON. We made appropriate adaptations so that they could operate in SDM-EON. The MDP-QoS algorithm as the INCREASER-QoP considers the traffic differentiation. The CaP-DPP algorithm as the INCREASER-QoP has a dedicated path protection mechanism. SBPPMC, as the INCREASER-QoP, uses a shared path protection mechanism. Finally, it is worth noting that for the best visualization, in the figures, the loads are presented on a scale of 1:1000.

Figure 2 shows the BBR of the algorithms for the USA (Figure 2(a)) and NSF (Figure 2(b)) topology. In the two topologies, we can observe that the BBR produced by INCREASER-QoP is smaller than that produced by the other algorithms. This difference is even more significant when considering the other algorithms that include protection (CaP-DPP and SBPPMC). While INCREASER-QoP starts bandwidth blocking at a load of 300 and 250 erlangs, the algorithms with the second-highest loads start blocking at 200 erlangs for the USA and NSF topologies, respectively. When compared with CaP-DPP and SBPPMC algorithms, the best performance of INCREASER-QoP results from its awareness of traffic

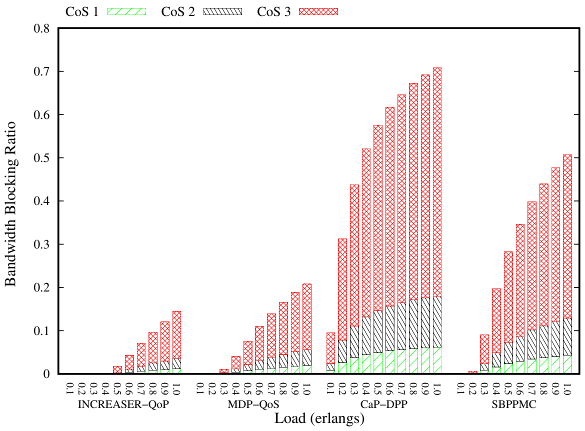


(a) USA

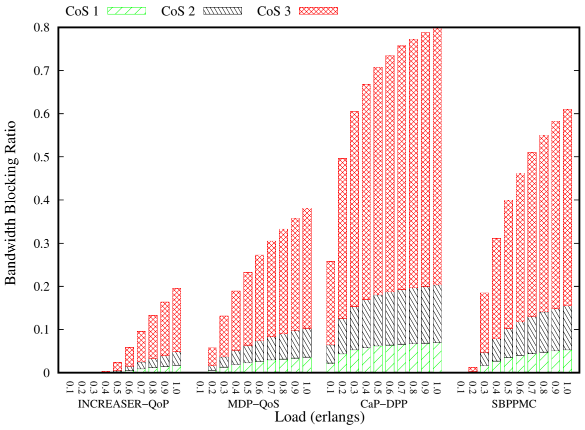


(b) NSF

Fig. 2. Bandwidth Blocking Ratio



(a) USA



(b) NSF

Fig. 3. Bandwidth Blocking Ratio by CoS

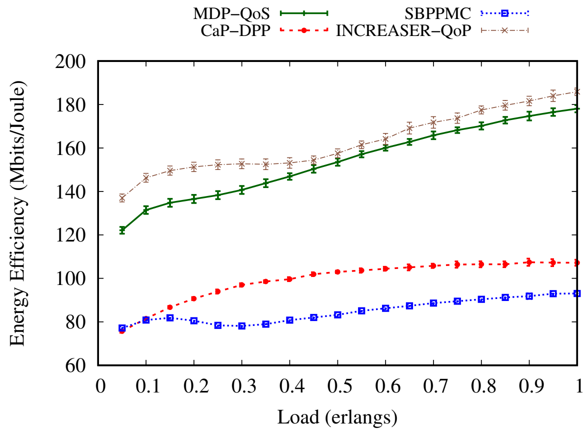
differentiation and the use of protection paths with the preemption technique. The BBR values of the MDP-QoS are closer to the BBR values of the INCREASER-QoP because the MDP-QoS does not consider the protection of flows, which results in significant resource savings and working with service degradation. Even so, the difference between the BBR of INCREASER-QoP and the BBR of MDP-QoS reaches two and three orders of magnitude in the USA and NSF topologies, respectively.

Figure 3 shows the blocking probability by class of service for the USA (Figure 3(a)) and NSF (Figure 3(b)) topologies. The difference in BBR produced by the INCREASER-QoP and those of the other algorithms is evident, especially those with a protection mechanism (CaP-DPP and SBPPMC), highlighting the low BBR for high priority traffic. While INCREASER-QoP presents maximum values of bandwidth blocking between 10% and 20%, the other algorithms reach maximum blocking probability above 50% for topologies, with the CaP-DPP reaching a blocking value close to 80% for the NSF topology. The higher blocking probabilities for the NSF topology, due to the lower connectivity of NSF nodes.

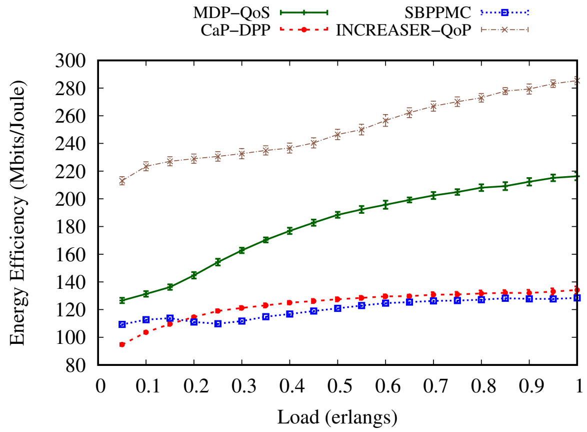
Figure 4 shows the energy efficiency as a function of the load. We can see that both for the USA topology (Figure 4(a)) and the NSF topology (Figure 4(b)), the INCREASER-QoP algorithm produces the most significant energy efficiency concerning the other algorithms that use protection mechanisms. This advantage is a consequence of the other algorithms with protection mechanisms not using preemption. This means that a large part of the spectrum is allocated but remains idle without data traffic. Compared with MDP-QoS, we note that INCREASER-QoP has the advantage for the NSF and USA topology. However, this advantage is not significant in the USA topology considering both algorithms' energy efficiency, which converges to closer values under the 450 erlangs load. This convergence occurs because while MDP-QoS deals with the scarcity of network resources by degrading services, INCREASER-QoP tends to allocate paths with more intermediate nodes, consuming more energy.

V. CONCLUSION

In this paper, we have proposed an algorithm called INCREASER-QoP, which uses different classes of service to provide resources reasonably to network requests, reducing spectrum consumption for protection and proposing a



(a) USA



(b) NSF

Fig. 4. Energy Efficiency

spectrum release tool according to the need for high priority requests. We evaluate the INCREASER-QoP algorithm was evaluated for different topologies and loads compared to other algorithms that employ protection and routing. In the performance evaluation, we could see the advantage of using a combination of DPP and SBPP techniques to protect SDM-EON networks by recognizing different levels of QoP. Furthermore, when using the preemption technique, it was possible to observe a significant reduction in the probability of blocking requests, given the lower consumption of optical resources, reaching up to 4 orders of magnitude difference compared to other protection algorithms.

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