Resilient Routing for SDM-EON as a Crucial Enabler for the Future Networks

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Abstract. *The rise of new Internet technologies and applications has exposed the limitations of current photonic networks in meeting the requirements of the next-generation Internet. Space-division multiplexing elastic optical networks have emerged as a solution to tackle this. However, these networks must also incorporate resilient mechanisms to handle today's enormous data. This study proposes efficient and reliable solutions to address the future growth of internet traffic. The proposed solutions were extensively compared to existing approaches using performance metrics. Results demonstrate their effectiveness in boosting advanced optical networks.*

1. Introduction

The emergence and popularity of high bandwidth and low latency network applications, such as high-definition video streaming, gaming, Internet of Things, and others, has increased exponentially in recent years [Devi et al. 2023, Haider et al. 2023]. Furthermore, during social isolation resulting from the COVID-19 pandemic, there was a significant traffic increase in the backbone network, mainly caused by the significant increase in network applications and online collaborations in various sectors. For instance, teleconferencing applications and online games grew by 300% and 400%, respectively [Devi et al. 2023]. Additionally, during the pandemic, telemedicine is essential to improving health professionals' safety and the scarcity of hospital space for face-to-face care. Given this perspective, there is a need for an efficient infrastructure to support the increasing network traffic growth and meet the different Quality of Service (QoS) requirements of current and emerging applications.

The optical transport technology is a crucial enabler for new scenarios of networks due to its high capacity, speed, and low transmission delay [Dias et al. 2023]. However, current optical networks that make up the Internet backbone are inflexible, causing poor resource utilization, high costs, and incompatibility for the scalability of new technologies of networks. The recent emergence of the Space-Division Elastic Optical Networks (SDM-EON) paradigm has become promising for flexible, programmable, and dynamic 5G transport network support. Even with the technological advances, it is essential to note that these networks are still subject to failure, whether caused by natural disasters or criminal attacks [Rak et al. 2021]. The two main resilience paradigms in the literature are protection and restoration. Protection mechanisms consist of proactive approaches, i.e., allocating backup paths during routing and resource allocation of requests [Rak et al. 2021]. On the other hand, restoration mechanisms are based on reactive approaches, i.e., treating failures only after they occur.

With the pre-allocated protection path, in the event of failures in the primary path, the network forwards the flow through the backup path [Rak et al. 2021]. In this sense, protection mechanisms have a considerable advantage regarding connection recovery time. However, their main disadvantage is the consumption of resources by backup paths for each connection. The reactive approach is more spectrally efficient since the network only allocates backup paths when necessary. However, the recovery time from failures with restore mechanisms is relatively high due to the re-routing. This recovery is not guaranteed, as no resources may be available at the failure [Stapleton et al. 2018].

When considering the presence of high-priority traffic on the network, it is more appropriate to use protection mechanisms to maintain network resilience, taking into account the main advantages of this paradigm [Stapleton 2019]. Most of the works proposed in the literature do not consider implementing protection tools to mitigate the data loss problem. On the other hand, even though some of the works in the literature propose solutions that consider the protection problem in SDM-EONs, such works do not show the main disadvantage of these mechanisms, *i.e.*, the overload caused by the excessive consumption of underutilized resources [Ferdousi et al. 2020].

Solutions to the Routing, Modulation Level, Spectrum, and Core Allocation (RMSCA) problem, which include resiliency provisioning, are of paramount importance for SDM-EON due to the massive amount of data that can be lost in case of optical path failures due to the high transmission rates in these networks. Therefore, there is a need to develop new mechanisms that reduce network overhead and ensure efficient recovery against failures. This document summarizes the goals and contributions of the Course Completion Work entitled: Priority-Aware Traffic Routing and Resource Allocation Mechanism for Space-Division Multiplexing Elastic Optical Networks developed at the Federal University of Pará, Brazil. In general, the research addresses the problem of routing and resource allocation efficiently when considering the resilience scenario in a heterogeneous traffic SDM-EON. The results produced by this research pushed forward the state-of-the-art in Space-Division Multiplexing Elastic Optical Networks by proposing various algorithms of protection considering different mechanisms and demonstrating the advantage of using the proposed algorithms compared to other approaches in the literature.

The rest of the document is structured as follows: Section 2 summarizes the limitations of literature solutions for SMD-EONs. Section 3 details the main goal of the Course Completion Work. Section 4 presents and discusses the results obtained in the simulations. Section 5 lists the publications of the Course Completion Work. Finally Section 6 concludes the document.

2. Related Works

Few studies on SDM-EON deal with the differentiated allocation of resources for network resilience. Furthermore, no work considers a protection mechanism to provide different Quality of Protection (QoP) levels in SDM-EON. Here we consider several ways to deal with this problem, among them through the use of *(i)* preemption; *(ii)* traffic priority, QoS differentiation, and so on.

Hai [Hai 2020] introduced the concept of Quality of Service (QoS)-aware protection, making it possible to separate flows into best-effort and premium traffic. This strategy guarantees only premium traffic, allowing fast recovery of this type of connection. However, the authors do not consider SDM-EON and do not use a preemptive protection policy to benefit high-priority optical paths. Oliveira and da Fonseca [Oliveira and da Fonseca 2017] proposed an algorithm to dynamically generate primary and backup paths using a shared backup scheme in SDM-EONs. However, the authors do not consider Classes of Service (CoS) and do not use a preemptive protection policy.

Zheng *et al.* [Zheng et al. 2023] focus on the routing, space, and spectrum assignment (RSSA) problems for the determination of the working path and backup path. They formulated the problems as two Mixed Integer Linear Programming (MILP) models to minimize the maximal frequency slot used (FS) index and the total number of backup FSs.

Zhu *et al.* [Zhu et al. 2021] introduced an RMSCA algorithm with floating traffic in SDM-EONs. The authors investigate resource allocation efficiency by minimizing crosstalk's impact on blocking probability. However, the proposed algorithm does not consider Quality-of-Protectiono (QoP), ignoring different priorities for requests.

Li *et al.* [Li et al. 2023] analyzed the multiplexing conditions of FIPP p-Cycle are analyzed and proposed a FIPP p-Cycle multiplexing algorithm to improve the utilization efficiency of backup resources. Then a segment protection algorithm for the working path is designed to decrease the service-blocking ratio as much as possible. In addition, by taking advantage of the traffic grooming strategy, the routing paths of services were optimized, yielding an effective decrease in the network blocking probability. Santos *et al.* [Santos et al. 2018] presented a model to deal 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 does not consider protection and does not consider SDM-EON.

Table 1 summarizes the main characteristics of previous works intended to analyze the routing and resource allocation model's main characteristics in terms of the use of Space Division Multiplexing (SDM), the use of different modulation formats (Modulation), protection provisioning (Protection), and Service Differentiation (DiffServ) in classes of service. Our state-of-the-art analysis found a need for resilience mechanisms in networks, such as SDM-EONs, with high traffic capacity to avoid large data losses. Therefore, by introducing spatial multiplexing into the concept of EON, the new RMSCA algorithms should support this new dimension, expanding the possibilities for routing connections, which will increase. Also, to further increase spectral efficiency, different modulation types are essential. However, when analyzing the related works', we found that few of them considered any of these characteristics. Only [Oliveira and Fonseca 2019], [Zheng et al. 2023], [Zhu et al. 2021] considered using SDM-EON, and only [Zhu et al. 2021], [Santos et al. 2018] considered adaptive modulation.

Based on the analysis of the related works, it is possible to conclude that none of the approaches can deal with the protection problem in SDM-EON while maintaining low network overhead. In this context, routing and resource allocation with protection and awareness of traffic priority is still an open problem.

Table 1. Related works summary

Approach	SDM	Modulation	Protection	DiffServ
[Hai 2020]			✓	✓
[Oliveira and Fonseca 2019]	✓		✓	
[Zheng et al. 2023]	✓		✓	
[Zhu et al. 2021]	✓	✓	✓	
[Li et al. 2023]			✓	
[Santos et al. 2018]		✓		✓

3. Goals and Contributions

Motivated by the limitations of literature solutions and the diversified applications and services that can be served by introducing optical networks for supporting technologies such as the Internet of Things (IoT) and 5G providing seamless interconnection among heterogeneous devices. The five routing and resource allocation algorithms for SDM-EON are presented and developed during the Course Completion Work period. The algorithms address protection in SDM-EON, considering the increase in spectral efficiency and the decrease in bandwidth blocking rate, in contrast to other protection approaches in the literature.

The first algorithm, QoP-NOODLES (*Diferenciação de **QoP** para RoteameNto, PrOteção, AlOcação **D**e NúcLeo e **ES**pectro*), aims to increase the acceptance rate and reliability of flows with a high level of relevance. It differs by dividing traffic into different levels of QoS, resulting in better use of optical resources. This algorithm recognizes three classes of service (high, medium, and low priority) and searches for a primary path for the request. If the request is CoS 1 or 2, the algorithm searches for a dedicated protection path; otherwise, the connection is established only with the primary path. If the optical path is unavailable in CoS 1 and 2 requests, the algorithm tries to release spectrum to meet the request demand. A detailed description of these solutions is presented in [Lopes et al. 2020].

The second algorithm, ESPECTRO (*RotEamento e Alocação de RecurSos com Mecanismo de **P**rotE**ç**ão **C**ienTe da P**R**ioridade de Tráfeg**O***), uses a traffic priority mechanism for resource allocation and protection in SDM-EON. It prioritizes traffic flows with high priority and protects them with more backup resources. The algorithm considers three classes of service and uses a preemptive approach, which means that it interrupts connections with lower priority to ensure resources for more critical connections. A detailed description of these solutions is presented in [Lopes et al. 2021b].

The third algorithm, INCREASER-QoP (*RoutINg Modulation SpeCtRum and CorE Allocation USing DiffERentiation by **QoP***), uses QoS differentiation to improve spectral efficiency in SDM-EON. It searches for routes that use less spectrum and allocates resources based on the classes of service of flows. In addition, INCREASER-QoP uses adaptive signal modulation and power adjustment to accommodate different transmission quality requirements. A detailed description of these solutions is presented in [Lopes et al. 2021a].

The fourth algorithm, TRAINEE (*RoTeamento e Alocação de **R**ecursos com

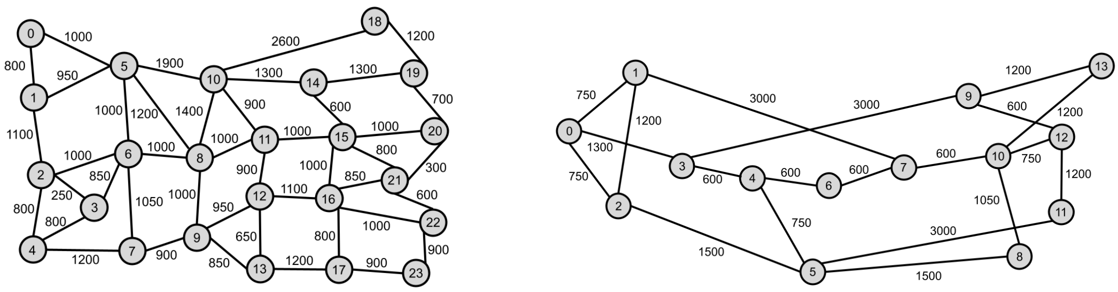
Proteção PreemptivA, CIeNte da PrioridadE de TráfEgo), utilizes preemptive protection and traffic prioritization to maximize spectral efficiency in SDM-EON. It divides connections into two classes of service, high and low priority, and allocates backup resources to high-priority connections. In addition, TRAINEE uses a resource reservation mechanism to ensure that high-priority connections have sufficient resources to protect them. A detailed description of these solutions is presented in [Lopes et al. 2022c].

Finally, the fifth algorithm, QUARANTINE (**Q**oP Differentiation, Ro**U**ting, Modul**A**tion, Co**R**e **AN**d Spec**T**rum Allocat**I**o**N** in SDM-**E**ON), provides routing, resource allocation, and protection for elastic optical networks with space multiplexing. It considers the heterogeneity of traffic, working with different classes of services with varying requirements, and uses QoP to optimize the allocation of resources. The traffic division offers protection features only for part of the connections, saving optical resources and increasing the network's energy efficiency. A detailed description of these solutions is presented in [Lopes et al. 2022a].

The work's contributions advance the state of the art of SDM-EONs and the routing and protection of optical networks. Therefore, the relevance of these contributions is to enable the evolution of SDM-EONs technology to increase the Internet transmission capacity and provide the network with robustness, allowing new applications with heterogeneous demands.

4. Performance Evaluation

To evaluate the performance of the proposed algorithms, the discrete event simulator FlexgridSim [Moura and Drummond 2018] was used. We developed a module that allows simulations with different classes of service that consider the traffic generated through the SDM-EON optical backbone. In simulations, we used topologies based on real scenarios. The first topology is USA (Figure 1(a) with 24 nodes and 43 links, and the second topology is NSF (Figure 1(b)) with 14 nodes and 25 links. Each algorithm was simulated according to the parameters of Table 2. The traffic generation was performed through the Poisson process, considering that CoS 1 corresponds to 8.3% of the traffic, CoS 2 corresponds to 16.7%, and CoS 3 corresponds to 75%, for algorithms that consider 3 classes of service. For the TRAINEE and QUARANTINE algorithms, which consider only two CoS, the ratio is 25% for CoS 1 requests and 75%. The ratio of protected and unprotected traffic follows the literature trend, which estimates that only 25% of traffic, on average, has a resilience requirement [Hai 2020].



(a) USA Topology

(b) NSF Topology

Figure 1. Topologies Used.

Table 2. Simulation Parameters

Parameter	Value
Load	(50 × x) *erlangs*[1] | x ∈ $\mathbb{N}$ ∀ 1 ≤ x ≤ 20
Bandwidth	25/50/125/200/500/750/1000 *Gbps*
# Cores	7
# Requests	100.000
# Slots FGB	1

Due to the limitation in the number of pages of this paper, we will only present the results for the Band Blocking Probability (BBR) metric per CoS and the Average Number of Hops per Optical Primary Path. Nevertheless, other metrics were used to evaluate the algorithms, such as Energy Efficiency and Flow or Optical Path Removal Probability. More details about these solutions can be found in the references of Table 3. The BBR per CoS is defined as the ratio between the blocked bandwidth for each CoS and the total bandwidth requested during the simulation. The Average Number of Hops in the Primary Path, in turn, is the ratio between the sum of the total hops of each established primary path and the total number of established primary paths.

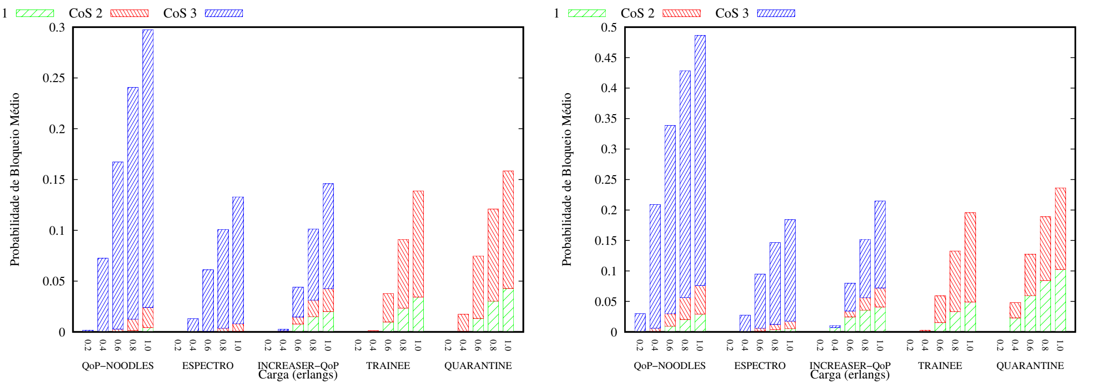
Figure 2 illustrates BBR results per CoS for the USA (Figure 2(a)) and NSF (Figure 2(b)) topologies. QoP-NOODLES algorithm demonstrates superior handling of high-priority requests due to its more invasive spectrum release approach, which promptly releases spectrum of an optical path before searching for free spectrum in other *K* routes. However, QoP-NOODLES algorithm exhibits the highest BBR among the presented algorithms.

Conversely, ESPECTRO algorithm delivers the lowest bandwidth blocking probability for high-priority requests and showcases lower BBR values overall. This is attributed to its consideration of adaptive distance modulation during flow routing and its thorough search for free optical paths in all *K* routes before attempting resource release.

INCREASER-QoP and TRAINEE algorithms yield results similar to the ESPECTRO algorithm, albeit with higher blocking occurrence at higher loads and higher BBRs for high-priority requests. This discrepancy arises from using preemption mechanisms in both INCREASER-QoP and TRAINEE algorithms. These facilitate optical spectrum release by directly affecting established optical paths instead of simultaneous disconnection of multiple requests (a reactive and less invasive approach). Nonetheless, a significant performance improvement is observed compared to other literature approaches, with a reduction of up to 60% in BBR.

QUARANTINE algorithm achieves low BBR values by employing traffic differentiation, adaptive modulation, and a spectrum release mechanism to conserve network resources. Consequently, the acceptance rate of high-priority flows increases substantially. Although the overall BBR of QUARANTINE is comparable to the preceding three algorithms, this is attributed to its more invasive spectrum release approach. However, when examining BBR by class of service, QUARANTINE's performance is inferior to the other algorithms except for QoP-NOODLES.

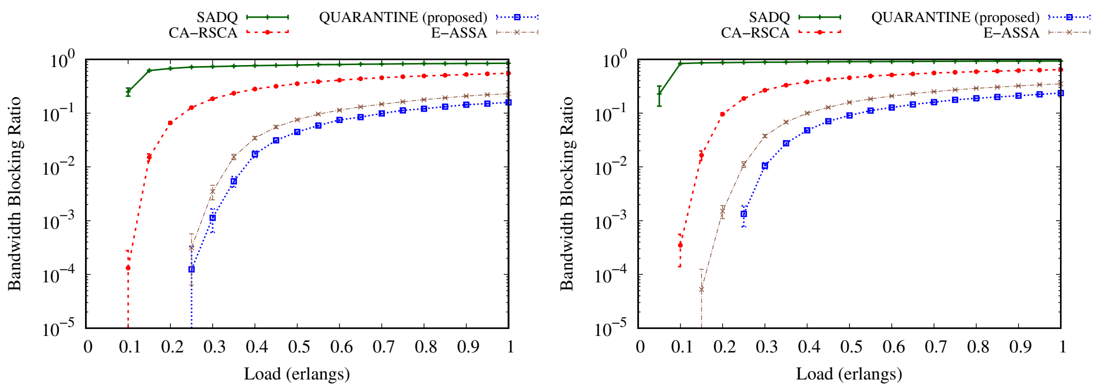
As a basis for comparison, Figure 3 illustrates the performance comparison be-



(a) USA (b) NSF

Figure 2. Probability of blocking the different CoS.

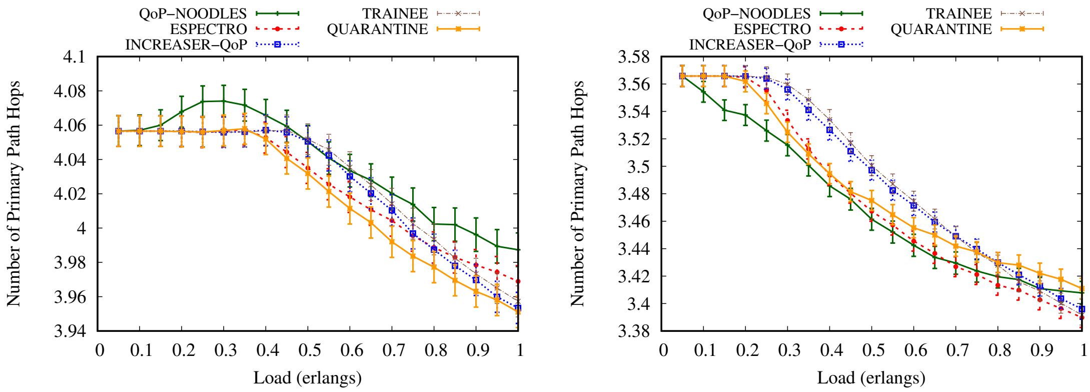
tween QUARANTINE, one of our algorithms, and other approaches from the literature. Figures 3(a) and 3(b) illustrate the BBR for the USA and NSF topologies, respectively. In the USA topology (Figure 3(a)), SADQ and CA-RSCA exhibit the worst performance, blocking requests above 100 erlangs. As network load increases, both algorithms converge in their blocking probabilities, blocking over half of the requests. Conversely, QUARANTINE performs the best, followed by E-ASSA, with request blocking starting below 250 erlangs. For the NSF topology (Figure 3(b)), SADQ, CA-RSCA, and E-ASSA begin blocking requests at 50, 100, and 150 erlangs, respectively. Notably, QUARANTINE outperforms the other algorithms, blocking below 250 erlangs. QUARANTINE consistently produces lower values in both topologies, even under the highest load of 1000 erlangs. Specifically, it achieves 16% BBR in the USA topology and 24% BBR in the NSF topology. These results demonstrate QUARANTINE's efficient resource allocation, combining traffic differentiation and the release of optical resources. Traffic differentiation minimizes resource allocation for non-protection paths, while resource release prioritizes critical traffic, resulting in higher acceptance rates.



(a) USA (b) NSF

Figure 3. Probability of blocking

In Figure 4, we present the results of the number of hops in the primary path for the USA (Figure 4(a)) and NSF (Figure 4(b)) topologies. It can be noted that the average number of hops in the USA topology remains higher than that of the NSF topology throughout the load range. This can be explained by the higher connectivity of the USA topology, which allows for a higher request acceptance rate, but with more hops. The compared algorithms follow the same decreasing trend in the number of hops. The QoP-NOODLES algorithm stands out in the difference between its results in the two topologies, as it has the highest number of hops in the USA and the lowest in the NSF. This phenomenon occurs due to the spectrum release mechanism of QoP-NOODLES, which, unlike the others, tries to release a spectrum band immediately after identifying it as occupied, without visiting the next K routes found by the KSP algorithm, in conjunction with the difference in topology connectivity.



(a) USA (b) NSF

Figure 4. Number of primary path hops.

5. Publication

The solutions presented in the Course Completion Work were published in 5 relevant conferences and two prestigious journals on computer networks and communication. Table 3 summarizes the result of the scientific initiation work up to the present moment. During this period, five conference papers and two journals were published. Notably, the scientific initiation student is the first author of all works.

Table 3. Papers Published as Results of the Course Completion Work

Reference	Publication	Qualis
[Lopes et al. 2020]	WPERFORMANCE 2020	B4
[Lopes et al. 2021b]	SBRC 2021	A4
[Lopes et al. 2021a]	IEEE Latincom 2021	B1
[Lopes et al. 2022e]	REIC 2022	C
[Lopes et al. 2022b]	SBRC 2022	A4
[Lopes et al. 2022a]	Computer Networks 2022	A1
[Lopes et al. 2022d]	NFV-SDN 2022	A4

6. Conclusions

This document summarizes the contributions of the Course Completion Work, which addresses the issues of protecting space-division multiplexing elastic optical networks. The main contributions of the Course Completion Work include five algorithms that use different classes of service to provide resources to network requests, reducing spectrum consumption for protection, and a module that allows simulations with different classes of service that consider the traffic generated through the SDM-EON optical backbone. Finally, the knowledge produced during research has been featured in several top-tier venues regarding scientific publications or short courses.

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