Resilient Routing for SDM-EON as a Crucial Enabler for the New Traffic Generation

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Abstract. *The introduction of new technologies and applications connected to the Internet has demonstrated the inability of current photonic networks to provide resources for the next-generation Internet. One of the main proposals to deal with this problem today is space-division multiplexing elastic optical networks. However, to transport the massive amount of data that is being generated today, these backbone networks should provide efficient resilience mechanisms. In this way, this Course Completion Work contributes efficient and reliable solutions to meet the future rapid growth of Internet traffic. The proposed solutions were extensively compared with related work on performance measurement metrics. The evaluation results show that the proposed solutions are efficient, boosting the latest generation 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 appears as an essential solution 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 in terms of 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 there may be no resources 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 the implementation of 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 (SDM-EON) 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 SDM-EON 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 SDM-EONs. Section 3 details the main goal of the Course Completion Work. In Section 4, the results obtained in the simulations are presented and discussed. 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 levels of Quality-of-Protection (QoP) 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 soo one.

Hai [Hai 2020] introduced the concept of Quality of Service (QoS)-aware protection, making it possible to separate flows into best-effort traffic 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 with the objective of minimizing 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 the efficiency of resource allocation by minimizing the impact of crosstalk on blocking probability. However, the proposed algorithm does not consider 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.

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.

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 **De** 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 quality of service (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 (*Rot**E**amento e Alocação de Recur**S**os com Mecanismo de **P**rot**E**ção **C**ien**T**e da **PR**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 (*Rout**IN**g Modulation Spe**C**t**R**um and Cor**E** **A**llocation U**S**ing Diff**ER**entiation 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 (*Ro**T**eamento e Alocação de **R**ecursos com Proteção Preemptiv**A**, C**I**e**N**te da Prioridad**E** de Tráf**E**go*), 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 with 24 nodes and 43 links, and the second topology is NSF with 14 nodes and 25 links. Each algorithm was simulated according to the parameters of Table 1. 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 trend of the literature, which estimates that only 25% of traffic, on average, has a resilience requirement [Hai 2020]

Table 1. Simulation Parameters

Parameter	Value
Load	$(50 \times x)$ *erlangs*[1] $\mid x \in \mathbb{N}\ \forall\ 1 \leq x \leq 20$
Bandwidth	25/50/125/200/500/750/1000 *Gbps*
# Cores	7
# Requests	100.000
# Slots FGB	1

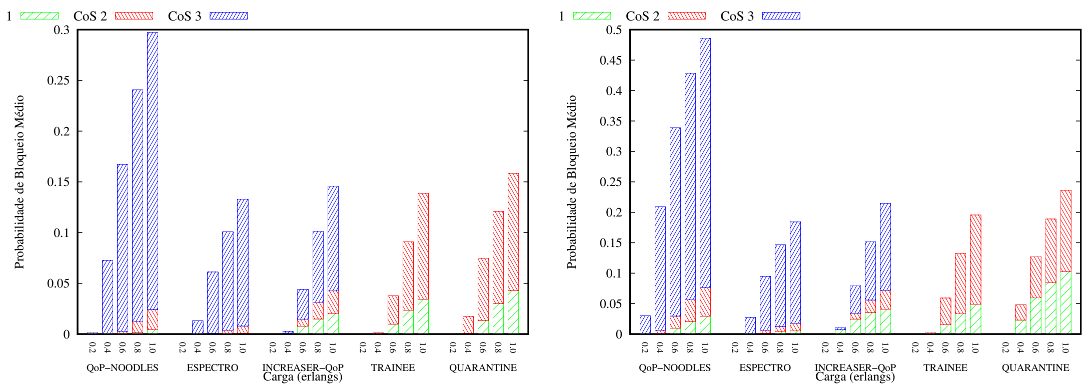
Due to the limitation in the number of pages of this paper, we will only present the results for the Band Blocking Probability (BBR) metric per CoS. Nevertheless, other metrics were used to evaluate the algorithms, such as Energy Efficiency, Flow or Optical Path Removal Probability, and Average Number of Hops per Optical Path. More details about these solutions can be found in the references of Table 2. The BBR per CoS is defined as the ratio between the blocked bandwidth for each CoS and the total bandwidth requested during the simulation.

Figure 1 shows the BBR results per CoS for the USA (Figure 1(a)) and NSF (Figure 1(b)) topologies. We can note that the QoP-NOODLES algorithm is the one that handles high-priority requests better. This is because it has a more invasive spectrum release approach, releasing the spectrum of an optical path before even looking for free spectrum in the other K routes found. Nevertheless, the QoP-NOODLES algorithm has the highest BBR among the presented algorithms.

The ESPECTRO algorithm, on the other hand, is the one that delivers the lowest bandwidth blocking probability for high-priority requests and presents the lowest BBR values. The BBR of the ESPECTRO algorithm is lower because it considers adaptive distance modulation during flow routing and because ESPECTRO searches for free optical paths in all K routes found before trying to release resources.

The INCREASER-QoP and TRAINEE algorithms produce results close to those of the ESPECTRO algorithm. However, they start their blocking at higher loads and produce higher BBRs for high-priority requests. This occurs because both INCREASER-QoP and TRAINEE algorithms use preemption mechanisms to enable optical spectrum release, acting directly on already established optical paths rather than disconnecting several requests simultaneously (a reactive and less invasive approach). Nevertheless, when comparing proposed algorithms with other literature approaches, the performance gain is significant (reaching up to 60% less BBR).

The QUARANTINE algorithm produces low values because it employs traffic differentiation, adaptive modulation, and a spectrum release mechanism to save network resources. This results in a significant increase in the acceptance rate of high-priority flow on the network. When we look at the total BBR of QUARANTINE, we see that it is close to the BBR of the other three algorithms that preceded it. This is explained by the use of a more invasive spectrum release approach. However, when we look at BBR by class of service, we see that its performance is worse than the other algorithms except for QoP-NOODLES.



(a) USA

(b) NSF

Figure 1. Bandwidth blocking ratio by CoS

5. Publication

The solutions presented in the Course Completion Work were published in 5 relevant conferences and 2 prestigious journals on computer networks and communication. Table 2 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 2. 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 providing protection in SDM-EON. 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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