Advanced Techniques for Resource Allocation and Routing in SDM-EONs

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Abstract. *The rapid growth in the number of Internet users, connected devices, and data-intensive services is pushing current optical network infrastructures to their limits, creating a demand for scalable, adaptive, and high-capacity solutions. Elastic Optical Networks (EONs) and space-division multiplexing (SDM) technologies have emerged as promising alternatives to traditional WDM systems, offering improved flexibility and capacity at the cost of increased network management complexity and physical-layer impairments. In this context, SDM-enabled Elastic Optical Networks (SDM-EONs) introduce challenging Routing, Modulation, Spectrum, and Space Allocation (RMSSA) problems. This work proposes the SimpleSimSDM simulation platform and a set of novel RMSSA approaches for SDM-EONs. Two space and spectrum allocation policies, CAD-BA and PAPAA, are introduced to balance bandwidth blocking, crosstalk, and fragmentation, while a routing strategy, MCC-FT, leverages multiple degradation metrics to reduce bandwidth blocking caused by localized node saturation.*

1. Overview

By 2029, an additional two billion people are expected to gain Internet access, with internet traffic growing five-fold over the same period [Nokia 2023]. Accordingly, the number of devices connected to the Internet has surged dramatically, with recent reports projecting the number of Internet of Things (IoT) devices alone to reach 500 billion by 2030. Everything from smartphones and laptops to IoT sensors and industrial equipment is being incorporated into vast, interconnected networks. This rapid growth has introduced an era where our homes, cities, factories, and even farms are becoming ”smart”, and relying on a constant stream of data to function efficiently [De Alwis et al. 2022].

As a result, the growing number of connected devices and the increasing complexity of services are pushing the limits of today's network infrastructure. Without significant advancements, current systems may struggle to keep up, highlighting the need for scalable, adaptive, and high-capacity networks to meet future demands. Many current strategies aimed at addressing the growing demand issue require a departure from traditional wavelength division multiplexing (WDM) to achieve higher network capacity [Ítalo Brasileiro et al. 2020]. In this context, novel network architectures propose to enhance network efficiency by leveraging the spectral resources of existing network infrastructure more flexibly or by expanding optical transport networks through additional channels for optical signal traffic.

The former approaches represent Elastic Optical Networks (EON), where available bandwidth is divided into narrow frequency slots, creating a fine grid for more flexible resource allocation. However, this introduces new network degradation factors, such as the allocation os resources at highly disjointed positions in the spectrum, *i.e.* increased fragmentation. The latter approaches may utilize Multi-Mode Fibers (MMFs), propagating multiple light modes within the same core, or Multi-Core Fibers (MCFs), adding multiple cores to the fiber for concurrent communication between nodes. However, these approaches introduce modal dispersion and inter-core crosstalk (CpS).

In order to achieve greater capacity and allocation flexibility new research proposes SDM-EONs as viable replacements for current WDM-based optical networks in different contexts, be it for long-distance connections or for data center communication, given their objective advantages. Additionally, it is an important challenge to decide the best path to be traversed inside of a given topology and to balance it with a modulation format (*mf*) that yields the best bits per symbol *BPS* performance, where the physical distance between nodes plays an important role, along with spectrum availability and continuity and contiguity compliance. Mismanagement of any of the aforementioned factors can greatly harm network performance. The set of SDM-EON related problems that encompasses all of the above network management aspects is known as Routing, Modulation, Spectrum, and Space Allocation (*RMSSA*) and its research has been very active in recent years [Dixit et al. 2021].

In [Oliveira 2025], we propose a simulation platform and several approaches to tackle all of the aforementioned RMSSA problems in SDM-EONs. In Chapter 4, we present our own simulation platform for straightforward prototyping and testing of RMSSA approaches in realistically constrained SDM-EONs. In Chapter 5, we propose *CAD-BA* and *PAPAA*, two space and spectrum allocation approaches that utilize multi-directional spectrum allocation and adjacent-core avoidance strategies to balance BBR, crosstalk (XT), and fragmentation. In Chapter 6, we present *MCC-FT*, a routing approach that employs multiple network degradation metrics to balance network load across the entire topology, significantly reducing bandwidth blocking due to localized node saturation.

This work is organized as follows: Section 2 summarizes recent developments in optical network architecture, highlighting the improvements in capacity and flexibility made possible by SDM-EON, as well as the current challenges in SDM-EON management that motivate this research. Section 3 provides a high-level view of what this research work aims to achieve. Section 4 delves further into the specific network management problems that this research work improves upon. Section 5 presents recent literature that both contextualizes our approaches within the broader research field and highlights our contributions. Section 6 succinctly describes the most prominent experimental results achieved by our approaches. Lastly, Section 7 lists the publications.

2. Motivation

As new applications test the limits of current-generation optical network architecture, with considerable growth projected to happen in the near future, SDM-EONs become a promising successor for their greater capacity and flexibility. However, despite SDM-EONs' advantages, this architecture is not devoid of drawbacks particular to it, since multiple spatial channels introduce interference in the form of XT, caused by light-path placement at adjacent cores, and fine granularity allows for unsystematic light-path placement within a core, leading to higher fragmentation.

Since routing, modulation, core and spectrum assignment policies are not directly transferable from the network architectures that precede SDM-EON given their fundamental differences in features and organization, the development of these policies is an active research field. In this context, we propose novel solutions to RMSSA in SDM-EONs that explore the gaps in the current state-of-the-art.

In this research work, we endeavor to gain deeper insights into effective strategies for optimizing RMSSA in SDM-EONs, addressing key challenges such as fragmentation and inter-core crosstalk while considering the constraints imposed by real-world network conditions. A crucial aspect of this investigation is the intricate interplay between mf selection, transmission reach, and XT sensitivity. These trade-offs require advanced resource allocation strategies that dynamically balance transmission reach, crosstalk mitigation, and spectrum fragmentation to ensure optimal network performance.

Additionally, we develop a flexible and efficient simulation platform that not only facilitates the prototyping and refinement of RMSSA algorithms but also enables their thorough evaluation under realistic traffic scenarios. By incorporating accurate models for physical-layer impairments and network constraints, this platform will provide a robust environment for testing and comparing different approaches, ultimately guiding the development of more efficient and resilient SDM-EON architectures.

3. Objectives

The research in [Oliveira 2025] offers novel RMSSA approaches for SDM-EONs, along with a new framework for simulating, prototyping and testing new algorithms in this network architecture. Below we go into more detail on what this research work attempts to achieve.

- Develop a modular framework that allows the simulation of SDM-EONs with easy integration to modern data-science and machine-learning open-source libraries for straightforward prototyping of RMSSA solutions.
- Develop multi-policy, fragmentation and XT-aware heuristic for resource allocation in SDM-EONs.
- Develop a multi-criteria, XT-sensitive flexible topology approach for routing in SDM-EONs

4. Contributions

This research comprehensively addresses the Routing, Modulation, Spectrum, and Spatial Allocation (RMSSA) problem in SDM-EON management. It does so by introducing novel heuristics for core selection and spectrum allocation that explicitly target the underlying dynamics responsible for crosstalk and fragmentation, which ultimately lead to increased request blocking. Through extensive comparative analysis, the proposed approaches consistently demonstrated highly competitive performance, outperforming relevant baselines across multiple metrics and thereby advancing the state of the art.

In addition, this work introduces a novel routing and modulation format selection approach that dynamically updates the network topology based on a weighted aggregation of network factors. This method effectively balances network load, substantially reduces node saturation, fragmentation, and crosstalk, and significantly increases the number of requests the network can accommodate while preserving overall network stability.

To enable rigorous development, implementation, and evaluation of SDM-EON management strategies, this research also delivers a simulation platform capable of realistically reproducing the constrained operation of SDM-EONs. The platform incorporates a virtual control plane and facilitates efficient prototyping, implementation, and systematic comparison of network management approaches.

Overall, the findings and experimental results clearly demonstrate the potential of SDM-EONs as a next-generation optical network architecture. This work advances the state of the art by more effectively leveraging SDM-EONs' flexibility and capacity while mitigating their primary degradation factors. Beyond establishing new performance baselines, it contributes a robust and extensible development platform that can be readily adapted to support future research in the field.

5. Related Work

In this section, we review the key literature relevant to the various domains of our research, providing a comprehensive overview of existing work in the field. The sections are organized to cover current SDM-EON simulation platforms, routing policies, and core and spectrum allocation strategies. We also highlight the contributions and drawbacks of current approaches in contrast to the proposed policies.

5.1. Resource Allocation Policies

A significant corpus has been dedicated to the various challenges surrounding SDM-EONs implementation, but few focus on allocation policies.

In Zhang *et al.*, three approaches were proposed to reduce request blocking in SDM-EONs. LB-RMA, for routing and mf assignment, surveys the spectrum and attempts first-fit allocation for the least-cost path between source and destination nodes, weighted by spectrum occupation. FA-SCA adopts a fragmentation metric for spectrum and core assignment. Lastly, LBFA-RMSCA merges both approaches for maximum performance. Unlike the proposed research, the example above uses super-channels that violate traditional contiguity constraints to achieve lower request blocking. No novel attempt is made to manage resource allocation [Zhang et al. 2021].

Yousefi *et al.* propose three novel algorithms to mitigate XT and BBR in SDM-EONs: Min Cross, Min Frag, and Mod Frag Cross. The first two algorithms trade off between mitigating fragmentation at the cost of greater XT and vice-versa, while the third balances both metrics. These algorithms do not account for the dimension, nature, or position of available spectrum regions within each core, making core-level allocation decisions [Yousefi and Ghaffarpour Rahbar 2020].

Lacerda *et al.* present two novel resource allocation and core selection algorithms for SDM-EONs. SBA mitigates XT caused by requests in adjacent cores, and CBA positions requests in cores with lower occupancy. Unlike the proposed policies, SBA does not attempt to delay core activation, only adopting a similar bi-directional sequential allocation logic. CBA chooses the core to be allocated by the lowest mean spectrum overlap but does not attempt allocation precisely at non-overlapping regions. There is also no mechanism to reduce spectrum fragmentation [Lacerda et al. 2021].

Vasundhara *et al.* introduce the FCA-RCSA algorithm that aims to optimize resource utilization by sorting path-core pairs by their fragmentation coefficient (fc) during the allocation process. However, the algorithm primarily focuses on minimizing fragmentation without explicitly addressing inter-core crosstalk and bandwidth blocking as comprehensively as our proposed policies. By incorporating core-activation delay, bidirectional allocation, and shadowed area avoidance mechanisms, our methods not only mitigate fragmentation but also reduce inter-core crosstalk and bandwidth blocking [Vasundhara et al. 2023].

5.2. Simulation Tools

In recent years some tools have been proposed with features that in one way or another overlap with the simulator proposed in Chapter 4. Below, we analyze the ones that are most similar to the proposed simulation tool, highlighting their similarities and underscoring how our approach contributes to the state-of-the-art.

Moura and Drummond propose the FlexGridSim, a discrete simulation tool programmed in java for SDM-EON simulation and testing that allows the adoption of multiple MCF configurations for the prototyping and testing of provisioning approaches that has been widely adopted in the literature for SDM-EON resource provisioning research in recent years [Moura and Drummond]. Unlike the proposed approach, this tool has no streamlined way of comparing and graphing results, nor does it allow for easy visualization of the tested topology. It is also not compatible with some of the most widely used libraries for scientific purposes, which makes longer pipelines harder to implement and run.

Costa *et al.* present the ONS, a discrete simulation tool programmed in Java for allocation approach testing in networks of the WDM and EON architectures. The ONS provides an environment for testing Routing and Wavelength Assignment (RWA) and Routing, Modulation Level and Spectrum Allocation (RMLSA) approaches. Unlike the proposed approach, the ONS does not allow setting up an MCF, thus space-division multiplexing is not possible out-of-the-box. As a result, it also does not account for inter-core crosstalk as one of its metrics. As it is programmed in java, it lacks integration to some of the more modern scientific libraries and does not possess graphing capabilities [R. Costa et al. 2016].

Júnior *et al.* offer a Python simulation tool for the development and testing of resource provisioning approaches in SDM-EONs that accounts for noise and XT and offer some data logging capabilities. In contrast to our approach, where an XML serves as an straightforward blueprint to the topology, in this tool all topology data is hard-coded into the simulator itself, which greatly reduces the ease to test novel approaches in different scenarios. It also adopts random distributions for call generation, unlike what is practiced in the literature [Júnior et al. 2022].

5.3. Routing Policies

Routing in SDM-EONs requires finding a path between two nodes to satisfy a given bandwidth request. Although optimal least-cost paths are achievable through approaches such as the Dijskstra algorithm, cost-minimization often relies in physical-distance or number of hops, which, in SDM-EONs, often leads to paths that, while being the shortest, are very inefficient. This occurs due to shortest-path allocation tendency of repeatedly including certain shorter length links, creating bottlenecks. Also, since path-length limits mf choice, conventionally, the most efficient mf possible for a given path-length is automatically selected, which might impair the remaining spectrum's ability to effectively allocate resources. Below, we summarize recent research that tackles these challenges, and compare it to the approach proposed in Chapter 6.

In Zhang *et al.*, three novel complementary approaches were proposed to reduce request blocking in SDM-EONs. LB-RMA, for routing and mf assignment, surveys the spectrum and attempts first-fit allocation for the least-cost path between source and destination nodes, weighted by spectrum occupation, irrespective of path length, position, or the number of hops required to traverse the path. FA-SCA adopts a fragmentation metric from the literature as criterion for spectrum and core assignment. Lastly, LBFA-RMSCA merges both approaches for maximum performance. Unlike the proposed research, the aforementioned example resorts to super-channels that violate traditional contiguity constraints to achieve lower request blocking. Additionally, at no point, more than one criterion is combined in order to calculate least-cost path, nor a novel approach is made to manage resource allocation. [Zhang et al. 2021].

In Petale and Yeung two online and two offline RMSSA approaches are proposed. Among the online solutions, Tridental Resource Assignment (TRA) is a multi-criteria approach that combines capacity loss, spectrum utilization and location of the spectrum into a single tridental coefficient (TC), paired with offline priority-based path selection to compute the best candidate modulation-core-spectrum triplet. SWARM serves as a simplified, more efficient version of TRA that groups cores based on the number of neighbors and applies first-fit for spectrum allocation. Besides being more computationally intensive, the aforementioned approaches require an offline element, while the proposed approaches work completely online and dynamically update link weights in order to achieve more efficient routing [Petale and Subramaniam 2023].

Vasundhara et al. propose an RMSSA approach for SDM-EONs that calculates a fragmentation coefficient (FC) metric based on the continuous aligned slot ratio and uses it to rank Dijkstra shortest-paths, as well as individual fiber cores, then attempts first-fit spectrum allocation at the path-core pair of minimum FC. Unlike the proposed approach, this algorithm relies entirely on link-length for least-cost path calculation, only subsequently applying a second criterion for path selection, and does not actively place requests on the spectrum, thus limiting its versatility in reducing important metrics, such as bandwidth blocking ratio and inter-core crosstalk [Vasundhara et al. 2023].

Yu et al. offer two XT-sensitive approaches for core and spectrum assignment in SDM-EONs, one static and the other dynamic. Both *CSA-SS* and *CSA-FF* use a K-SP algorithm for routing. *CSA-SS* uses an auxiliary spectrum-sensitivity matrix to estimate XT and sort candidate frequency-slot blocks prior to allocation, while *CSA-SS* attempts first-fit allocation of spectrum resources. Unlike our approach, the algorithms described above do not propose any novel load-balancing or BBR mitigation, xt-avoidance, nor any other network enhancing technique beyond the spectrum allocation phase [Chen et al. 2023].

Rezaee et al propose an RMSSA solution for SDM-EONs. Their approach includes a multi-criteria XT-aware routing mechanism (XTAR), which combines an 'XT-effect' metric with link length for link weight calculation, paired with an XT-aware resource allocation algorithm. However, this approach does not offer any mechanism that aims at balancing load across the network topology. It also relaxes a fundamental SDM-EON constraint in order to make one of its mechanisms feasible [Rezaee et al. 2024]

In summary, current research on RMSSA for SDM-EONs includes various approaches which broadly share some functionality with what was offered in this approach, such as the utilization of multiple criteria for optimal path estimation, which is also present in some formulation in [Petale and Subramaniam 2023], [Vasundhara et al. 2023], [Rezaee et al. 2024]; load-balancing, which is employed by [Zhang et al. 2021] and [Petale and Subramaniam 2023]; and XT-aware spectrum mapping, which also exists in [Chen et al. 2023].

However, no study was able to produce a multi-criteria RMSSA approach for network load-balancing which operates in a realistically constrained network, that is, a network under continuity and contiguity constraints, where mf selection must adhere to transmission reach restrictions and light-path establishment must obey strict XT thresholds, so that each allocation complies with the physical limitations of SDM-EONs, while ensuring resource efficiency. Unlike previous studies, our approach achieves optimization across multiple layers of decision-making, offering a robust and scalable solution to address the complex challenges of routing, modulation, and spectrum allocation in SDM-EONs.

6. Results

In this section, we summarize our experimental results, which are analyzed in detail in Chapters 4, 5, and 6 in [Oliveira 2025]. These findings show that we were able to provide a competitive simulation platform for the efficient design and testing of RMSSA approaches for realistically constrained SDM-EONs. Additionally, we propose a multi-policy approach that successfully addresses resource allocation in SDM-EONs under multiple constraints across a wide load interval, without compromising reliability. Finally, we present a comprehensive routing solution that accounts for multiple factors when selecting the optimal transmission path and achieves higher allocation efficiency by more effectively distributing network load across the entire topology.

Design and Testing in SDM-EONs: In order to enhance our development process we developed the SimpleSim SDM-EON, a discrete simulation platform for the design and testing of RMSSA approaches to SDM-EON. The use of standardized data-formats for topology design and data sampling along with the included graphing capabilities facilitate not only the development of approaches from the 'ground-up', but also the incremental adjustment and tweaking of existing algorithms for optimal performance. SimpleSim works with specialized modules that, together, perform the multiple functions required for optical network simulation. By the compartmentalization and assignment of specific tasks to modules written in actively developed and widely used scientific libraries, we ascertain a higher degree of credibility and longer maintainability to the simulation tool. Future developments to this tool might include support for Machine Learning-Aided (ML-Aided) allocation approaches, improved QoT calculation and physical impairment simulation.

Resource Allocation: To solve resource allocation in constrained SDM-EONs, we developed two allocation policies: Core Activation Delay Bi-Directional Allocation (CAD-BA) and Precise Adjacent-Core Parallel Allocation Avoidance (PAPAA). These policies combine strategies for efficient SDM-EON resource allocation, such as adjacent core activation delay, bi-directional allocation, and precise adjacent-core overlapping allocation avoidance. These mechanisms reduce network degradation caused by spectrum fragmentation and inter-core crosstalk, resulting in lower request blocking rates and greater stability under heavy loads. Our simulation results show that the proposed policies were consistently successful in exceeding the approaches used for comparison. CAD-BA showed the best, most balanced performance, by reducing BBR the most (a reduction of up to 30% under heavy loads, and 22% overall) while keeping fragmentation and CpS at comparatively low numbers while PAPAA achieved the second best BBR reduction (of 19% overall), while reducing CpS noticeably and maintaining acceptable fragmentation levels. Furthermore, as demonstrated the experimental results, the proposed policies managed to excel at different metrics in distinct load intervals, which highlights our approach's flexibility. Further details on the blocking mitigation achieved relative to the our baselines in percentage points are shown in Table 1.

	PAN TOPOLOGY		**NSF TOPOLOGY**	
Policy	**FCA-RCSA**	**MinCross**	**FCA-RCSA**	**MinCross**
CAD-BA	16%	22%–30%	17%–20%	24%–43%
PAPAA	13%–19%	19%	16%–20%	24%–45%

Tabela 1. BBR mitigation compared to baselines

Multi-Criteria Routing: To further improve SDM-EON performance, we developed a routing approach that dynamically calculates link-weight across the network topology based on the combination of important network factors. Next, it produces a map of all slots in the spectrum for a given path which, if allocated for a given modulation format, would not disrupt any currently active light-paths, nor would it be subject to crosstalk that exceeds known thresholds for the intended modulation format. The resulting approach allows for least-cost routing that self-balances network load, reduces inter-core crosstalk and ultimately greatly mitigates request blocking by up to 90% compared to the literature. Further details on the blocking mitigation achieved relative to the our baselines in percentage points are shown in Table 2.

	USA TOPOLOGY			**NSF TOPOLOGY**		
Policy	**LB-RMA**	**FCA-RCSA**	**MCC-NFT**	**LB-RMA**	**FCA-RCSA**	**MCC-NFT**
MCC-FT	40%–52%	77%–90%	30%	26%	76%	40%

Tabela 2. BBR mitigation compared to baselines

7. Research Accomplishments

The research work described in [Oliveira 2025] is the culmination of extensive investigations into the RMSSA problem set, with each major development presented at prominent conferences or published in relevant journals within our research field. Our work on core and resource allocation policies was first submitted and published as a conference paper [Oliveira et al. 2024] (A4 Qualis) and later appeared in the conference proceedings. A significantly improved version (see Chapter 5), featuring algorithms adapted for enhanced performance and more meaningful comparisons with the existing literature, was presented at the *ACM Symposium on Applied Computing* (ACM SAC) [Oliveira et al. 2025] (A2 Qualis).

Our research on the multi-criteria routing approach, detailed in Chapter 6, has also produced highly promising results. The paper describing its methodology and comparative simulation results was published in the *Journal of Internet Services and Applications* (JISA) [Oliveira and Oliveira 2025] (A2 Qualis). Lastly, our research also yielded results in the form of collaborations with researchers from interconnected research fields, in which the exchange of knowledge led to the publication of [Bastos et al. 2023].

8. Closing Remarks

Overall, the results of this research demonstrate that the proposed approaches effectively address the RMSSA problem in realistically constrained SDM-EONs. By combining a dedicated simulation platform with novel resource allocation policies and a multi-criteria routing strategy, this work achieves significant reductions in blocking probability, fragmentation, and inter-core crosstalk across a wide load range. The experimental evaluation confirms that the proposed solutions consistently outperform relevant baselines while maintaining network stability under heavy traffic conditions.

Beyond its technical results, this work advances the state of the art by providing new performance baselines and a flexible simulation framework that supports reproducible research and future extensions. The publication of its main contributions in well-established venues highlights their relevance to the field. Collectively, these contributions strengthen the case for SDM-EONs as a viable next-generation optical network architecture and establish a solid foundation for continued research in advanced network management strategies.

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