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Multi-Criteria, crosstalk-sensitive flexible topology approach for routing in SDM-EONs

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Abstract In recent years, the demand for high-capacity, flexible optical networks has driven significant advancements in network design, especially within Space-Division Multiplexing Elastic Optical Networks (SDM-EONs). These networks are expected to efficiently handle the increasing volume of data traffic while minimizing issues such as inter-core crosstalk and request blocking, which can degrade performance. To address these challenges, we propose an RMSSA (Routing, Modulation, Spectrum, and Space Assignment) approach specifically for SDM-EONs. Our method dynamically calculates link-weight across the network topology by considering a combination of critical network factors, enabling a flexible topology that self-balances network load prior to every incoming resource request. Next, our approach maps all slots in the spectrum guaranteed to not disrupt already allocated light-paths, while being under the crosstalk threshold for any desired modulation format, which is enabled by the adoption of precise slice-based crosstalk estimation (PS-XT). This multi-criteria, crosstalk-aware routing strategy significantly reduces inter-core crosstalk, leading to more efficient resource utilization and a considerable reduction in request blocking, ultimately enhancing the overall performance and reliability of SDM-EONs. Our comparative results show average reductions in request blocking of up to 77% for the load interval tested and up to 90% at lower loads, compared to approaches from the literature. Crosstalk was also reduced in over 36%, on average, and up to 60% at lower loads while fragmentation was mitigated in up to 11%.

Keywords: Optical Networks, Routing , Space-Division Multiplexing Elastic Optical Networks

1 Introduction

The number of individuals with access to the internet has been steadily increasing, bringing more users online and fueling the demand for digital services. Additionally, the number of devices connected to the internet has surged dramatically, so much so that the number of IoT devices alone is projected to reach 500 billion by 2030 [Zikria *et al.*, 2021]. 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 [Li *et al.*, 2021] [Abadía *et al.*, 2022] [Kalsoom *et al.*, 2020] [De Alwis *et al.*, 2022].

Projections point to an additional two billion individuals with internet access until 2029, and a five-fold increase in internet traffic is expected to the same period [Nokia, 2023]. 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 handle the future demands.

Conventional systems, which rely primarily on Wavelength-Division Multiplexing (WDM), are increasingly unable to cope with the escalating bandwidth requirements and dynamic traffic patterns. This has driven the evolution towards more advanced and flexible solutions, particularly in the realm of Space-Division Multiplexing Elastic Optical Networks (SDM-EONs) [Brasileiro *et al.*, 2020].

SDM-EONs represent a breakthrough in optical network design, providing a means to scale capacity by employing multiple spatial channels in parallel optical fibers, thereby multiplying the available bandwidth [Tode and Hirota, 2014]. Unlike traditional optical networks that are confined to spectral domains, SDM-EONs add a spatial dimension to the network, enabling the simultaneous transmission of multiple signals over distinct cores within a single optical fiber (within the same cladding) [Awaji *et al.*, 2017].

This spatial expansion, combined with the elasticity of spectrum allocation, allows SDM-EONs to adapt to varying traffic demands dynamically, enhancing both spectral efficiency and flexibility in resource management. However, the benefits of SDM-EONs come with their own set of challenges. One of the most significant is inter-core crosstalk, a phenomenon where signal interference occurs between adjacent spatial channels or cores within the same optical fiber. Crosstalk can severely degrade the quality of transmission, leading to increased bit-error rates and reduced data throughput [Halder *et al.*, 2022]. Additionally, the dynamic nature of SDM-EONs, while advantageous for flexibility, also presents a higher risk of spectrum fragmentation, that might lead to request blocking despite there being enough resources available [Khorasani *et al.*, 2023].

As more users and applications compete for network resources, inefficient routing and resource allocation can result in under-utilization of the available spectrum, leading to higher request blocking and diminished network performance. To address these challenges, the development of sophisticated resource allocation and management strategies is crucial. Routing, Modulation, Spectrum, and Space Assignment (RMSSA), refers to the network management problems at the core of SDM-EON optimization research. It encompasses policies to decide how data flows through the network, which modulation formats to use, how spectrum is assigned, and which spatial channels are utilized. An efficient RMSSA algorithm must consider multiple factors, including network topology, traffic demand, crosstalk mitigation, and load balancing, to ensure that the network operates efficiently under diverse conditions [Sharma *et al.*, 2022] [Vasundhara *et al.*, 2023][Heera *et al.*, 2022]. As SDM-EONs continue to evolve and expand, the ability to dynamically manage resources across multiple spatial channels will become increasingly important. Our research addresses the challenges of crosstalk and request blocking as well as points towards future research possibilities in SDM-EONs, a critical next-generation optical network architecture capable of supporting the ever-growing demands for data transmission in a hyper-connected world.

In recent years, researchers have made significant advancements in RMSSA, particularly in developing routing approaches which employ multiple criteria to calculate optimal paths for routing in SDM-EONs. The criteria were either applied in combination, to produce composite link weights for a given topology, or sequentially, as a means of ranking candidate paths for allocation. The metrics used vary greatly, with Petale and Subramaniam [2023] combining capacity-loss, spectrum utilization and spectrum location, while in Vasundhara *et al.* [2023], the authors use link-length and fragmentation sequentially to rank the best paths, and in Rezaee *et al.* [2024] a crosstalk metric and link-length are employed to calculate or rank the optimal paths. In Zhang *et al.* [2021] and Petale and Subramaniam [2023], the authors propose load-balancing mechanisms which account for spectrum occupancy for routing. In Chen *et al.* [2023], an XT-aware spectrum mapping mechanism is proposed to mitigate crosstalk and reduce crosstalk-related request blocking.

This article introduces a novel RMSSA strategy specifically tailored for SDM-EONs where continuity and contiguity constraints, as well as transmission reach and strict crosstalk thresholds are enforced. Our approach dynamically calculates link-weight across the network topology by combining important network parameters. As it continuously evaluates these factors, our algorithm produces a topology customized for every request in a way that minimizes crosstalk and balances network load. This self-balancing capability is particularly crucial for SDM-EONs, as it allows the network to respond flexibly to traffic variations and avoid congestion, ultimately reducing the likelihood of request blocking. In addition, our approach maps free-spectrum prior to allocation in a manner that guarantees that the crosstalk threshold for the incoming light-path is respected and that no active light-paths are disrupted by utilizing precise, slice-based crosstalk calculation *(PS-XT)*.

The proposed RMSSA strategy offers significant improvements in network performance, mitigating request blocking by 77% over a wide load-interval, peaking at a 90% reduction for lower loads. Inter-core crosstalk saw a sustained reduction of 36% over the tested interval, peaking at a 60% reduction for lower loads and fragmentation was reduced in up to 11%.

This work aims to demonstrate that, by integrating a flexible topology routing approach with XT-awareness to an SDM-EON under continuity and contiguity constraints that enforces transmission reach restrictions to the adopted modulation formats and strict XT-thresholds it is possible to achieve superior performance, meeting the high-capacity demands of modern communication networks while maintaining high levels of reliability and efficiency. Through extensive simulations and performance evaluations, we illustrate the significant advantages of our approach, particularly in terms of reducing request blocking and crosstalk, and improving overall resource utilization, making SDM-EONs a viable and scalable solution for the future of optical networking.

1.1 Problem Statement

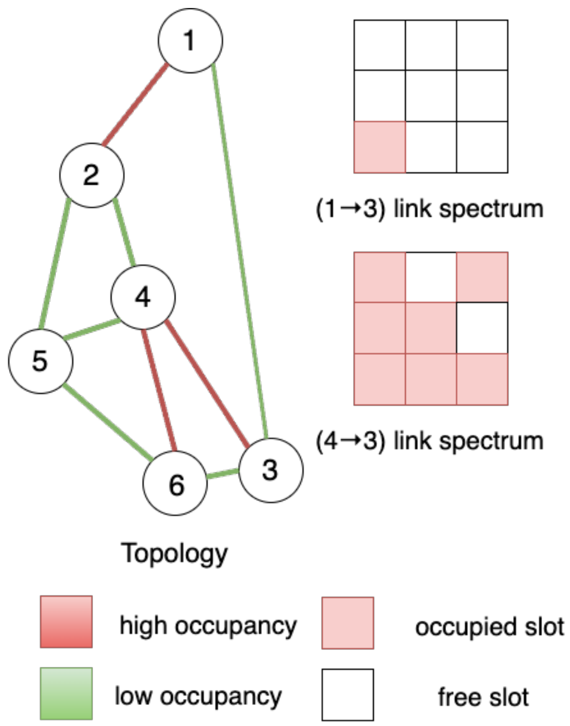


Figure 1. Network Topology

In order to better illustrate the problems tackled in this research, we provided a scaled-down, simplified version of the routing process in a multi-core fiber SDM-EON, with three cores per fiber and three slots per core. This network runs on the example topology illustrated in Figure 1

As Figure 2(a) illustrates, once a source-destination node-pair is decided, the required bandwidth is converted to slots, in compliance with the selected modulation format, and a request is sent for the shortest-path that connects both nodes so that a light-path can be established, as seen in Figure 2(b). Next, the available spectrum for every link in a candidate shortest path is procured, as illustrated in Figure 2(c), and the spectrum for the whole path is obtained by performing the Boolean *OR* operation across all individual links that

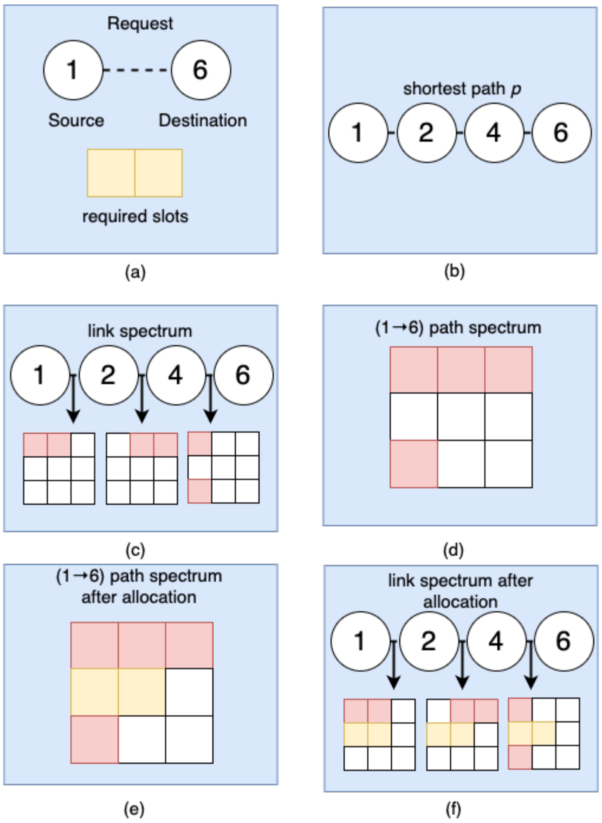


Figure 2. Routing Process

form the path (Figure 2(d)). Lastly, resource allocation is performed, as shown in Figure 2(e), raising spectrum occupancy for the links between source and destination, as in Figure 2(f).

Since routing is usually based on shortest-distance, load imbalance builds up in the network as shorter-distance links (in our example, the link connecting nodes 1 and 2) are repeatedly included in candidate shortest-paths and become too congested to efficiently serve requests, being promptly rejected, wasting computational resources and, more importantly, raising request blocking rates and other network deterioration metrics such as crosstalk and fragmentation [López *et al.*, 2016].

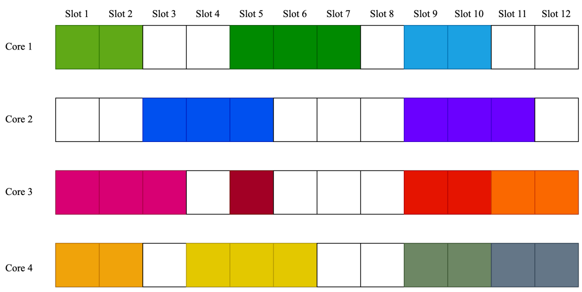


Figure 3. Spectrum Allocation Problems

For a clearer understanding of crosstalk and fragmentation, Figure 3 offers a more detailed abstraction for the spectrum of a given path, in a multi-core fiber with four cores and twelve slots, during dynamic resource allocation in an SDM-EON architecture. Every active light-path is represented by a set of connected slots that shares the same color. In this scenario, the adjacent cores to $core_i$ is $core_{i+1}$ and $core_{i-1}$, and so on. Crosstalk can be characterized as the interference caused by two (or more) active light-paths sharing at least one slot in adjacent cores. Crosstalk between non-adjacent cores is negligible. In our example, crosstalk is evident between adjacent cores $core_1$ and $core_2$, both with active light-paths which overlap in three positions: slots 5, 9 and 10. Without crosstalk mitigation measures, the number of requests blocked for exceeding the established crosstalk thresholds increases, with crosstalk thresholds lowering the more efficient a modulation format is.

Fragmentation measures the available spectrum distribution in a core, where it is desirable to have as many of the available slots as possible at neighboring positions in the core, which characterizes low fragmentation. As available slot blocks are split apart into smaller sections, fragmentation rises. In our example, a high fragmentation level is evident in $core_2$, which, despite having half its capacity available (six free slots out of a total twelve slots), cannot allocate any request that requires more than one-fourth of its total capacity due to the inefficient distribution of current allocations. High fragmentation levels may raise the number of requests blocked for lack of sufficient spectral resources, which specially harms the chances of long-distance requests that use less efficient modulation formats of being accepted.

In order to address load-balancing, crosstalk and fragmentation mitigation, this article introduces a novel flexible topology, crosstalk-aware routing approach specifically designed for SDM-EONs. The proposed approach aims to maximize the number of data requests that can be successfully served by efficiently managing the load distribution among the topology links while adhering to various network constraints, such as continuity, contiguity, transmission reach and crosstalk sensitivity.

1.2 Contributions

This article presents several key contributions that address crucial problems within the context of SDM-EONs.

- **Network Model**: Our network model adheres to continuity and contiguity constraints, and applies transmission reach restrictions for adaptive modulation format selection in multi-core fiber SDM-EONs. Modulation formats are crosstalk-sensitive and crosstalk is precisely calculated during execution for the whole network. This approach provides a testing environment that more closely mirrors real-world networks and the impairments they experience, particularly under heavy loads.
- **Routing Approach**: We propose a routing algorithm specifically designed to work within the aforementioned SDM-EON environment, which leverages multiple criteria in order to dynamically build a topology that better suits a request. As a result, the proposed algorithm balances network load, which lowers request blocking, crosstalk and fragmentation in the network compared to similar approaches.
- **Crosstalk-Aware Free-Spectrum Mapping**: Once a path that is decided, our approach builds a free-spectrum map that ensures strict crosstalk-thresholds are followed. This prevents any resource allocation pol-

icy from placing incoming requests in areas of the spectrum under more crosstalk than their modulation format would allow while preemptively avoiding the disruption of already active requests, which further assists mitigating request blocking.

To the best of our knowledge, ours is the only SDM-EON RMSSA solution that combines the aforementioned adherence to several strict, realistic network constraints, with the dynamic routing of call requests through a flexible topology, while using precise crosstalk estimation in order to accurately simulate crosstalk sensitivity across the network. By addressing these areas, the proposed solution significantly advances the state of SDM-EONs, contributing to more efficient, scalable, and adaptable network infrastructures.

1.3 Methodology

In this work, we propose a crosstalk-aware, flexible topology approach for routing and spectrum mapping designed specifically the SDM-EON architecture. Our methodology prioritizes rigorous statistical analysis to ensure accurate simulation results and fair comparisons with existing literature.

The core of our proposed solution is an algorithm that dynamically builds a topology tailored to every request by attributing a composite weight to every link in the network based on a combination of multiple network statistics. Next, our approach maps free-spectrum in a way that guarantees observance to strict crosstalk thresholds. This approach employs a flexible topology as a means to promote load balancing, consequently reducing request blocking, inter-core crosstalk, average network crosstalk and even fragmentation. Below, we outline the key components of our methodology:

- **Network Model:** We model the SDM-EON as a digraph where nodes can perform bi-directional communication through the optical links represented by the edges of the graph. The links support elastic bandwidth allocation and each link can be divided both spectrally and spatially to accommodate different requests.
- **Traffic Characterization:** The incoming requests are characterized by their bandwidth requirements and addressing, and are generated according to Poisson process between uniformly distributed source-destination link-pairs and transmission rates. The algorithm processes these requests in real-time, making adjustments to the topology and free-spectrum map at every request.
- **Optimization Strategy:** Our approach focuses on dynamically deciding a topology tailored to every request based on a combination of link-length, defined as the physical distance between any two nodes, and spectrum occupation, which quantifies the impact of active light-paths on the network's ability to provide resources for incoming call requests.
  The former metric ultimately limits the choice of modulation formats (see Figure 5) and is associated with higher request blocking due to transmission reach constraints. The latter metric, on the other hand, highlights link saturation, which indicates over-utilization and load imbalance across links. Since these metrics can conflict when used simultaneously in a least-cost approach, we adjusted their relative weights by incrementally emphasizing one over the other until the optimal experimental results were achieved for the tested topologies.
  Additionally, we incorporate a mechanism to generate a free-spectrum map that ensures safe allocation, *i.e.* allocation that does not disrupt active light-paths and does not endanger the incoming request by exposing either to crosstalk values beyond their tolerances.
- **Performance Metrics:** We evaluate the effectiveness of our algorithm using key performance metrics, including bandwidth blocking ratio, crosstalk-per-slot, average crosstalk and overall fragmentation. Simulations are carried out under varying traffic conditions to assess the algorithm's robustness and adaptability and the results are thoroughly analyzed.

By structuring our methodology around these principles, the proposed solution addresses the unique challenges of SDM-EONs and offers a scalable approach for improving network performance.

1.4 Organization of this Article

This article is structured as follows: Section 2 discusses in detail the *RMSSA* problem-set, highlighting the interplay between various network factors that guide the design of optimization policies for SDM-EONs. Section 3 presents a survey of relevant literature on the researched subject, underscoring the similarities to our approach and, in particular, how the proposed approach improves upon what we perceive as their shortcomings. Section 4 discusses the proposed approach in detail and includes a detailed description of all the steps it comprises, as well as several abstractions to better convey the working principles of our routing mechanism. Section 5 provides a detailed account of all the assessment criteria adopted, such as the physical layer parameters used, the simulation scenario description, error margins, considered metrics and, lastly, a detailed analysis of the comparative results obtained. Section 6 reaffirms this research's key contributions to the field, summarizes its comparative results and points towards future research developments.

2 RMSSA for SDM-EONs

Routing, Modulation, Space and Spectrum Allocation (*RMSSA*), describes a set of network problems crucial to the development of efficient SDM-EONs [Brasileiro *et al.*, 2020]. Routing requires procuring the best path between a source-destination node-pair in the network to serve a given request [López *et al.*, 2016]. Modulation format selection requires analyzing the relationship between efficiency and crosstalk-sensitivity, space allocation comprises all decisions necessary to select the best spatial channel for transmission, which, in the case of multi-core fibers, refers to the management of the multiple cores available [Winzer, 2014][Van Uden *et al.*, 2014]. Then, within a spatial channel, spectrum is allocated to the slots deemed more viable, after factors such as fragmentation and crosstalk are considered.

Once a source-destination node-pair and bandwidth are decided, and a request is sent, SDM-EONs require that a physical path connecting both nodes is found, along with a viable modulation format. Then, the available spectrum across a candidate path is procured and resource allocation is performed according to the criteria defined in the control plane, raising spectrum occupancy for the links that compose the path between source and destination.

Naturally, since routing frequently does not account for dynamic network factors, being usually static and relying on shortest-distance paths (see [Vasundhara *et al.*, 2023],[Chen *et al.*, 2023]), spectrum occupation imbalance builds up as shorter-distance links are repeatedly included in the most prominent shortest-path candidates and become bottlenecks to spectrum allocation to be promptly rejected, wasting computational resources and, more importantly, raising request blocking rates and other network deterioration metrics.

In Figure 7, Topology *(a)* illustrates this problem with the provided traditional, link-length weighted topology model, where the link that connects nodes 1 and 2 will always be included in any shortest-path that has *Node 1* as source-node for its very short length. The proposed approach avoids this problem by building a flexible topology (Topology *(b)*) that balances spectrum occupancy by dynamically changing link-weight, thus tailoring the topology itself to better serve a request. The proposed approach is described in Section 4.

Following the routing stage, the modulation format has to be decided. The more spectrally efficient a modulation format, the fewer frequency slots are necessary to serve a request, which leaves more resources for future light-path allocation. As seen in Figure 4, a request that requires one hundred slots for the *BPSK* modulation format would have required only half as many slots if the *QPSK* modulation format were to be used, then alternatively 34 slots if *8-QAM* were to be adopted and only 25 for *16-QAM*. However, greater efficiency has two major drawbacks, since the more efficient a modulation format is, the shorter its transmission reach, as illustrated in Figure 5, and more sensitive it is to crosstalk, as described in Table 2. Therefore, any policy for modulation format selection requires considering the delicate interplay between efficiency, transmission reach and crosstalk sensitivity.

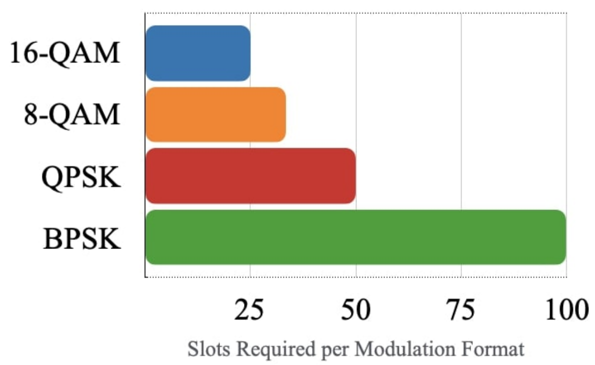


Figure 4. Modulation Format Efficiency

The next stage required for successful light-path establishment consists in *a.* selecting the spatial channel, which in this research is represented by one of seven cores in an hexagonal multi-core fiber (MCF) and *b.* placing the request within a region inside the spatial channel selected.

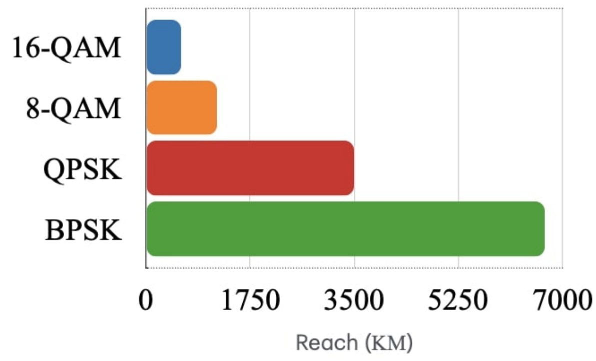


Figure 5. Modulation Format Transmission Reach

As illustrated in Figure 8, the optical fiber simulated in our research contains seven cores in an hexagonal arrangement within the same cladding that serve as spatial channels. Adjacent cores (connected by the two-way arrow signs) are cores mutually subject to inter-core crosstalk, *i.e.* allocated slots in one core will interfere with slots in the same indexes in all of its adjacent cores (as illustrated in Figure 9).

A viable region consists in frequency slots linearly connected within the same core and in sufficient number to satisfy the request. Figure 6 illustrates the continuity and contiguity constraints that must be followed for a successful allocation, where the incoming request for two frequency slots to be allocated in the path between source-destination nodes *a* and *c* has to be placed in two adjacent slots within the same core (contiguity) that are free for allocation in the exact same indexes for every link in that path (continuity), in our example *link 1* and *link 2*. Although *link 1* has enough resources that follow contiguity constraints at the region formed by the slots at $\{(1,2),(1,3)\}$ coordinates, as well as $\{(3,1),(3,2)\}$, allocation cannot succeed in those regions, since continuity is not guaranteed for *link 2*, where slots *(1,3)* and *(3,1)* are occupied. Therefore, the only remaining allocation option is the region $\{(3,2),(3,3)\}$, for complying with both constraints across the whole path.

3 Related Work

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 Dijkstra 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 modulation format choice, conventionally, the most efficient modulation format 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 Section 4.

In Zhang *et al.*, three novel complementary approaches were proposed to reduce request blocking in SDM-EONs.

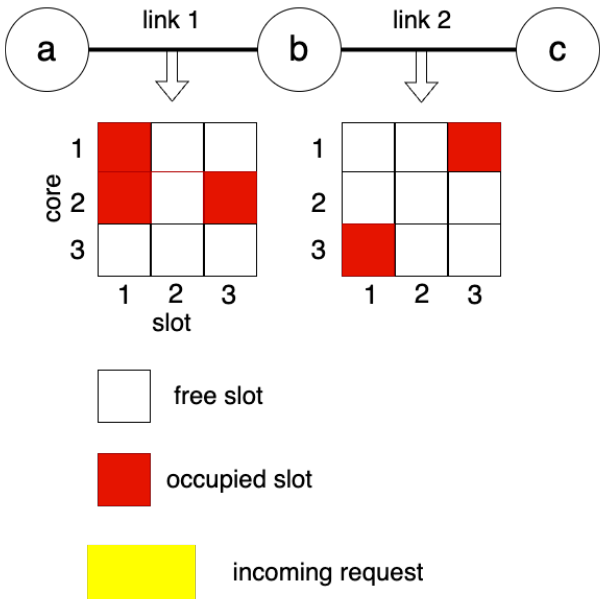


Figure 6. Continuity and Contiguity Constraints

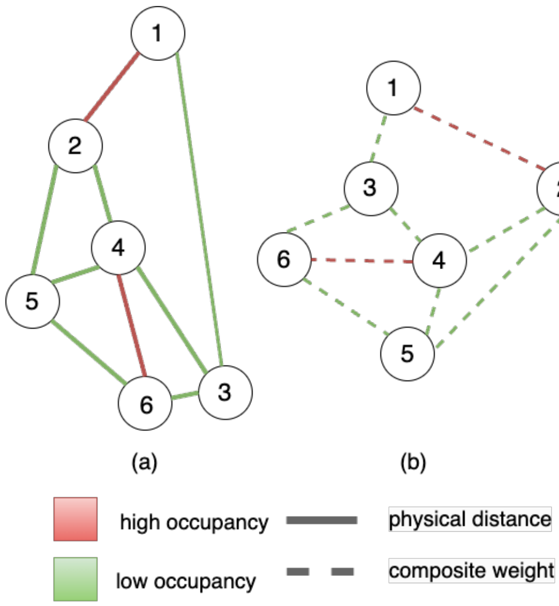


Figure 7. Routing Problem

LB-RMA, for routing and modulation format 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 crosstalk-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 crosstalk 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 routing approach for network load-balancing which operates in a realistically constrained network, that is, a network under continuity and contiguity constraints, where modulation-format 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 optimiza-

Table 1. Comparison of Works

Approach	Multi Criteria	Load Balancing	XT-aware Spectrum Mapping	Precise XT Measurement	Fundamental Constraints Adherence	Online
[Zhang *et al.*, 2021]		✓				✓
[Petale and Subramaniam, 2023]	✓	✓			✓	
[Vasundhara *et al.*, 2023]	✓				✓	✓
[Chen *et al.*, 2023]			✓	✓	✓	✓
Rezaee *et al.* [2024]	✓			✓		✓
Proposed Approach	✓	✓	✓	✓	✓	✓

tion 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.

4 Multi-Criteria, Crosstalk-Aware Flexible Topology Approach for Routing and Modulation Format Selection in SDM-EONs (MCC-FT)

In this section, we propose an RMSSA approach for SDM-EONs. Our approach 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 modulation format intended. The resulting approach allows for least-cost routing that self-balances network load, reduces inter-core crosstalk and ultimately greatly mitigates request blocking.

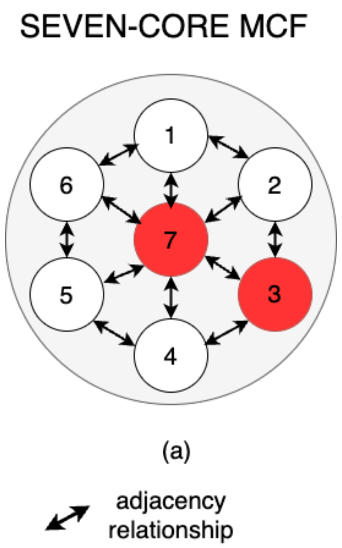


Figure 8. MCF Spectrum Organization

The Multi-Criteria, Crosstalk-Aware Flexible Topology *MCC-FT* approach dynamically updates topology weight to a linear combination of link-length and spectrum occupation, finds least-cost paths based on this new metric and produces a map of the total free-spectrum for the path that precisely

Algorithm 1 MCC-FT

Input: source-destination, transmission rate
Output: free-spectrum map
For l in L:
  calculate CW_l using Eq. 1
Find p shortest paths for (src, dst)
Find mf for each *path* in P
For p in P:
  For slot in spectrum
    For link l in p:
      Calculate $XT_{(c,p)}$ using Eq. 4
      For c' in C' of slot:
        If χ_A for c':
          Flag lp that contains c'
      If $XT(c,p)$ of slot $\leq XT_{\text{th}}(\text{mf})$:
        For f_lp in LP:
          If $XT(c,p)$ of $f\_lp > XT_{\text{th}}(\text{mf(f\_lp)})$:
            Slot is unavailable
            Continue to next slot
        Slot is added to free-spectrum map
  Attempt allocation
  If allocation is successful:
    allocate
    continue
  Else:
    continue to path $p+1$

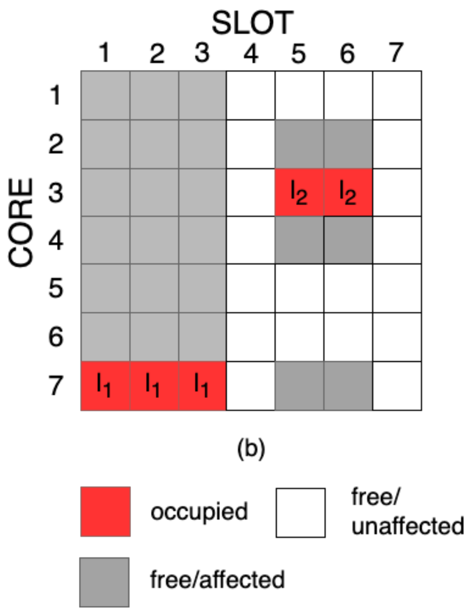


Figure 9. MCF Spectrum Organization

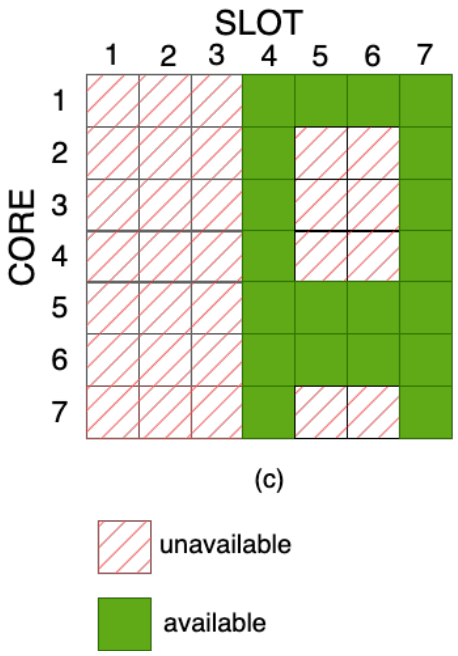


Figure 10. MCF Spectrum Organization

accounts for the impact of crosstalk *XT* in the allocation of a new light-path (*i.e.* a set of slots that satisfies a single request). Then spectrum allocation is performed by the *MMM* algorithm [Oliveira *et al.*, 2024], which avoids resource allocation on neighboring cores by classifying cores based on adjacency, prioritizing non-adjacent cores over adjacent ones, and determining light-path placement direction according to adjacency status.

As described in Algorithm 1, once a request is received, containing the source-destination node-pair and transmission rate, a topology-wise weight update is performed to define current link-weights (lines 1-2). The time complexity for this stage is equal to $O(|L| \cdot |spectrum|)$, where $|L|$ is the number of links in the network and $|spectrum_l|$ is the total number of spectrum slots in the MCF for any given link. Consequently, when scaled to include more links, it exhibits a linear behavior for any fixed-sized spectrum grid MCF. The new composite weight (CW) for any given link l is calculated as a weighted linear combination as shown in Eq. 1:

$$CW_l = \sum_{i=1}^{n} \left(\frac{\eta_i - \min(\eta_i)}{\max(\eta_i) - \min(\eta_i)} \right) \cdot w_i \quad (1)$$

Here, η represents the set of considered criteria $\eta = \{link\ occupancy, link{-}length\}$ and w is the set of weights that correspond to every criterion, such that $w = \{\frac{1}{2}, \frac{1}{2}\}$. $Link{-}length$ is the physical distance that separates any pair of nodes and $link - occupancy$ is equal to the ratio of occupied slots to free-slots in a given link. Therefore the links in the resulting topology, as shown in Figure7*(b)*, do not directly reflect the distance between nodes, but a combination of factors that, in the example provided, allow for least-cost paths that avoid high-occupancy links, balance network occupancy and mitigate request blocking.

To the resulting topology we apply Yen's Shortest Path Algorithm [Yen, 1971] in order to find a set P of candidate paths that minimize the total path composite weight (Algorithm 1, line 3), as defined in Eq. 2:

$$\sum_{l \in p} CW_l \quad (2)$$

The number of candidate paths (p) limits the number of times the spectrum availability mapping phase (lines 5 to 18) can be executed. Its complexity is $O(|P| \cdot |l| \cdot |spectrum| \cdot |C'|)$, meaning that as more candidate paths are considered, the spectrum must be queried more frequently. Additionally, as traffic grows $|C'|$ increases as well. After careful analysis, we observed that in the tested topologies, the call acceptance rate drops to virtually zero after querying the fourth shortest path. Thus we added an extra candidate as a safety margin and considered the five shortest candidate paths in order to enhance computational efficiency.

For every candidate path $p \in P$, we choose the most efficient modulation format *mf*, *i.e.* the *mf* that allows the greatest bandwidth with a transmission reach at least as long as the path-length. By choosing the most efficient *mf*, the number of required frequency slots can be greatly reduced (see Figure 4).

The next step requires producing the available spectrum for the path by verifying, for every free-slot, whether it can allocate a request for a given modulation format, for which two conditions must be met: *a.* crosstalk levels must be under the threshold for the modulation format and *b.* allocation must not disrupt active light-paths on adjacent cores by raising their crosstalk levels above their respective tolerances (Algorithm 1, lines 6 to 17).

To model network *XT* we adopted precise slice-based crosstalk estimation (PS-XT), for its better performance and accuracy [Zhang and Yeung, 2023] [Klinkowski and Walkowiak, 2018]. For PS-XT, let the *XT* for a light-path *lp* at a core *c* across path *p* be referred to as $XT(c, p)$, that can be calculated as described in Eq. 3:

$$\mathrm{XT}_{c,p} = \max_{\mathrm{fs} \in \mathrm{lp}} \left(\sum_{l \in p} \sum_{\mathrm{c'} \in \mathrm{C'}} \chi_A \cdot h \cdot |l| \right) \quad (3)$$

In accordance with the above equation, the *XT* value for all frequency slots *(fs)* in a given *lp* is equal to the maximum *XT* value for any of the *fs*s that forms it. The *XT* value for a single *fs* is the sum, for every link $l \in$ path *p* and for every adjacent core *c'* $\in$ *C'* (core-adjacency can be seen in Figure 8) of $\chi_A \cdot h \cdot |l|$, where χ_A is an indicator function that is equal to 1 if the adjacent core *c'* is occupied and 0 otherwise, *h* is the power-coupling coefficient and $|l|$ is the link-length.

Since the $\mathrm{XT}_{c,p}$ for an *lp* is equal to the maximum *XT* for any singular slot in the intended *lp*, our approach builds a free-spectrum map by considering one individual free-slot as a light-path, and verifying weather allocation is feasible for it using the most efficient modulation available for the transmission reach, then repeats the process for every free slot. Thus, we measure the *ps-xt* for a single-slot light-path with Eq. 4.

$$\mathrm{XT}_{c,p} = \sum_{l \in p} \sum_{\mathrm{c'} \in \mathrm{C'}} \chi_A \cdot h \cdot |l| \tag{4}$$

Figures 9 and 10 illustrate the free-spectrum generation process: in Figure 9 we show the current state of a given link, with two active light-paths (l_1 and l_2) allocated with a highly XT-sensitive modulation format, such as 64-QAM, and the respective slots in adjacent-cores whose allocation might disrupt l_1 and l_2, respectively (in gray). In Figure 10, the resulting free-spectrum map displays all slots whose allocation would not disrupt the already established light-paths, as well as maximum transmission reach and xt-threshold for the incoming light-path.

Finally, allocation is attempted for $path_p$ in the slots contained in its free-spectrum map, where a new light-path for the modulation format chosen is guaranteed to obey the aforementioned criteria of non-disruption of already established light-paths and of staying below the modulation-format threshold (Algorithm 1, line 18). If unsuccessful, $path_{p+1}$ will be queried and so on, until allocation is successful or the number of candidate paths is exhausted and the request is blocked.

5 Performance Evaluation

In this section, we provide a comprehensive explanation of the performance evaluation methodology we adopted, covering the simulation tools, simulation parameters, metrics used, and the benchmark algorithms.

5.1 Network Configurations

The adopted optical network architecture incorporates wavelength-selective switching optical add/drop multiplexers (OADM), space-wavelength granularity, and MIMO transceivers within a seven-core, hexagonal-shaped multicore fibers. Each core features a 320-slot spectrum grid, with each slot providing 12.5 Gbps capacity.

Links are defined as node pairs that allow bi-directional data communication. By default, Link weight denotes the physical distance between nodes within each topology, and the weight sum for any given path is used to verify adherence to maximum transmission reach for every modulation format. Our models prevent connections across free-slot regions spanning multiple cores (*i.e.* super-channels) to maintain continuity and contiguity constraints. The number of frequency slots required for a request depends on modulation (baud rate), which varies with the physical distance between nodes. Each request includes an additional slot as a guard-band.

Our simulations used four distance-dependent modulation formats: 16QAM, 8QAM, QPSK, and BPSK, with corresponding slot capacities of 62.5, 50, 37.5, 25, and 12.5 Gbps. The corresponding XT-thresholds and transmission reach for every modulation format can be found in Table 2, and their values were derived from [Klinkowski and Zalewski, 2019], with a slight adaptation in BPSK's transmission reach so as to guarantee the reachability of all links in the network for the topologies tested.

We assume no signal regeneration, thus requests that exceed the maximum transmission reach for the chosen modulation format are preemptively denied. We also adopt XT-thresholds for every modulation format so candidate light-paths can only be allocated if: *a.* resulting *XT* for the light-path does not exceed the threshold for the modulation format and *b.* light-path allocation does not disrupt neighbor light-paths beyond their respective *XT* thresholds.

$$h = 2 \cdot \left(\frac{\kappa^2 \cdot R}{\beta \cdot \Lambda} \right) \tag{5}$$

The power-coupling coefficient for $XT_(c,p)$ estimation is calculated as in the Eq. 5, where κ is the mode-coupling coefficient, *R* is the MCF bending-radius, β is the propagation constant and A is the core pitch. The approximate *h* value of 10^6 was adopted for the following reference values: $\kappa = 1277 \cdot 10^{-3}$ $R = 50\,\mathrm{mm}$, $\beta = 4 \cdot 10^6\,\mathrm{m}^{-1}$, $\Lambda = 40\,\mu\mathrm{m}$

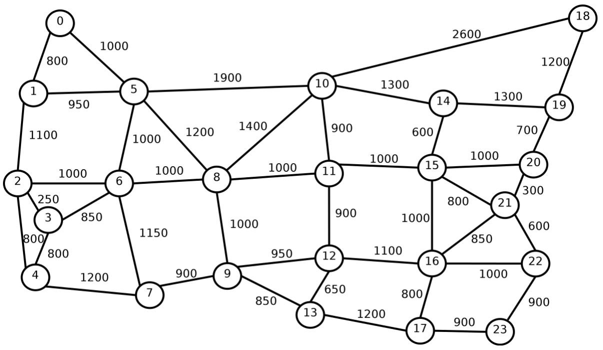
5.2 Scenario Description and Methodology

To evaluate the proposed approach, we emulated both network functions and operations using a simulated SDM-EON with a virtual control plane, generating performance results with a 95% confidence interval. Our simulation tool, SimpleSim SDM-EON, was fully developed in Python to ensure compatibility with modern network and data-processing libraries, enabling a streamlined simulation pipeline. It reproduces and extends the functionality of the widely adopted FlexGridSim framework Moura and Drummond [2025].

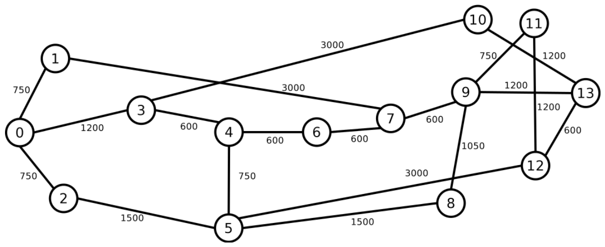
We perform 10^5 requests per simulation round, with each request containing a source and destination node-pair for unicast transmission. There always exists at least one path between source and destination with a length that does not exceed the maximum range for the *BPSK* modulation format (as stated in Figure 5). Traffic is modeled as a Poisson process between uniformly distributed source-destination link-pairs and transmission rates (the values adopted were 25 Gbps, 50 Gbps, 125 Gbps, 200 Gbps, 500 Gbps, 750 Gbps, and 1 Tbps). The request density values tested, measured in erlangs (E), varied between 50E and 600E, with 25E increments. The Poisson process was selected due to its widespread use in network modeling for call arrival processes, as seen in prior research Zhang *et al*. [2021], Petale and Subramaniam [2023], Oliveira and Da Fonseca [2022].

	BPSK	QPSK	8-QAM	16-QAM
xt-threshold (dB)	-21.7	-26.2	-28.7	-32.7
transmission reach (KM)	6700	3500	1200	600

Table 2. XT-Threshold and Transmission Reach for Different Modulation Formats



(a) USA



(b) NSF

Figure 11. Topologies

We simulated the USA topology (Figure 11(a)) with 24 nodes and 86 links, and the NSF topology (Figure 11(b)) with 14 nodes and 40 links. Each link weight represents the composite weight explained in detail in Section 4. Our results were compared with the *FCA-RCSA* and *LB-RMA* approaches from [Vasundhara *et al.*, 2023] and [Zhang *et al.*, 2021], respectively.

FCA-RCSA places a fragmentation coefficient (FC) metric at the center of their approach to routing, core selection and resource allocation. FCA-RCSA ranks shortest-path candidates and individual cores by their *FC*, then attempts first-fit allocation at the path-core pair in ascending order of *FC*. *LB-RMA* retires distance completely from routing and uses exclusively spectrum occupancy to weight topology links, then attempts first-fit spectrum allocation on the shortest-paths obtained. We also simulated scenarios where the flexible topology mechanism was deactivated (*MCC-NFT*) to highlight our approach's contributions to higher network efficiency.

5.3 Metrics

In order to measure our approach's performance we assessed four valuable metrics: bandwidth blocking ratio (BBR), crosstalk per slot ratio (CpS), average network crosstalk (XT), and fragmentation. *BBR* gauges how much of the total requested bandwidth could be provided as call density rises. It provides a more accurate assessment of network efficiency compared to the ratio of denied requests, as it considers the total bandwidth requested and denied, rather than just the number of calls. *CpS* measures network degradation caused by the simultaneous allocation of frequency slots on adjacent cores at the same positions. *XT* measures the average network crosstalk, considering the *PS-XT* values for every active light-path, and *Fragmentation* metric evaluates how disorganized or disjointed are the free-spectrum regions in the network.

While the ultimate goal is to serve as many requests and provide as much bandwidth as possible, which *BBR* measures, it is not sufficient to reliably convey network performance, since even in scenarios where all requests are served, inefficient resource management might manifest in the form of high fragmentation, where the remaining network resources are so irregularly distributed that they become effectively unusable. It may also appear in the form of high *CpS*, where modulation format choices are severely reduced or even nonexistent given the disproportional allocation of resources at neighboring positions across the available spatial channels. Crosstalk (*XT*) measures the average *PS-XT* value considering all active light-paths and depicts allocation performance across the whole network. Consequently, together these metrics show the interaction between different but complementary aspects of network management, and precisely express how the proposed approach influences network performance.

We calculate *BBR* as the quotient between the blocked bandwidth and the total requested bandwidth as described in Eq. 7.

$$BBR = \frac{\sum blockedbandwidth}{\sum totalbandwidth} \tag{6}$$

CpS was measured as described in Eq. 7

$$CpS = \frac{1}{|L|} \sum_{l \in L} \frac{1}{|S|} \sum_{s_{ij} \in S} \left(\chi_{A_{s_{i-1j}}} + \chi_{A_{s_{i+1j}}} \right) \tag{7}$$

Where L is the set of all links connecting the topology nodes, such that $L = \{l_1, l_2, \ldots, l_n\}$; S is the set of slots currently occupied in l_n's spectrum and their respective positions, such that $S = \{s_{0,0}, s_{4,2}, \ldots, s_{ij}\}$, and χ_A is an indicator function that equals 1 if a slot in the same position in adjacent cores is occupied and 0 otherwise.

The average topology crosstalk (XT) was measured as illustrated in Eq. 8

$$\text{XT} = \frac{1}{|L|} \sum_{l \in L} \frac{1}{|C| \times |S_c|} \sum_{c \in C} \sum_{s \in S_c} \text{XT}_{c,p} \tag{8}$$

Where L is the set of links that form the topology, such that $L = \{l_1, l_2, \ldots, l_n\}$, C is the set of cores belonging to every link l_n and S is the set of slots available to every core c_n. $\text{XT}_{c,p}$ represents the precise crosstalk estimation for the slot, measured according to Eq. 8

Spectrum fragmentation was measured according to Eq. 9:

$$\text{Fragmentation} = \frac{1}{|L|} \sum_{\text{link} \in L} \frac{1}{|\Phi|} \sum_{\substack{\phi \in \Phi \\ r \in R}} \chi_A \left(\frac{r}{\text{sc}} \geq \text{dimension}(\phi) \right) \tag{9}$$

Where L is the set of links in the topology, such that $L = \{l_1, l_2, \ldots, l_n\}$. Φ is the set of fragments (free-slot regions) in l_n's spectrum, such that $\Phi = \{\phi_1, \phi_2, \ldots, \phi_n\}$. R is a set of transmission rates practiced and sc is the transmission capacity for an individual slot. χ_A is an indicator function that equals 1 if the condition is true and 0 otherwise. $|L|$ is the number of links in the topology and $|\Phi|$ is the number of fragments (regions) in the spectrum.

5.4 Results

This section presents our experimental results for the *MCC-FT* routing approach for the topologies tested, illustrated in Figures 11(a) and 11(b). We compared our approach's performance to two policies from the literature, *FCA-RCSA* and *LB-RMA*, further discussed in Subsection 5.2. All loads are measured in erlangs (E).

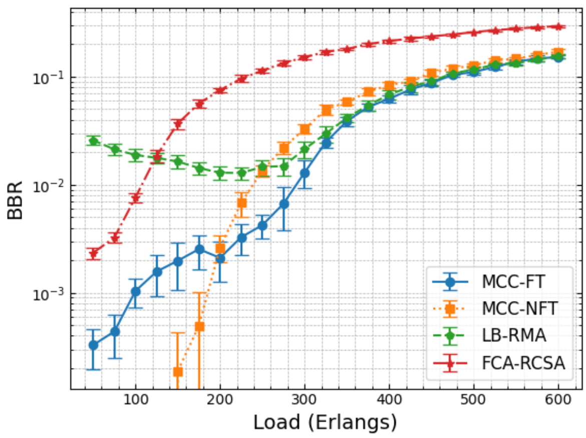


Figure 12. Bandwidth Blocking Ratio

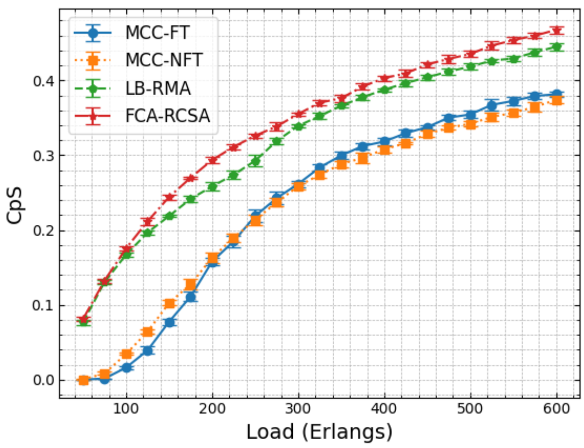


Figure 13. Crosstalk per Slot

Figures 12, 13, 14 and 15 illustrate network performance for the proposed multi-criteria routing approach in the USA Topology. Figure 12 shows the BBR for this topology, where the proposed *MCC-FT* was shown to perform 77% better than *FCA-RCSA* overall and up to 90% better for loads ranging from 50E to 375E. Compared to *LB-RMA*, our approach led to a reduction in 40% in overall *BBR* and up to 52% for loads between 50 to 475E. *MCC-NFT* managed to block, on

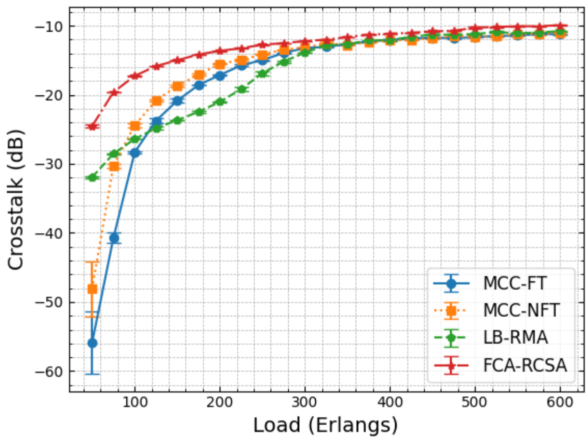


Figure 14. Average Crosstalk (DB)

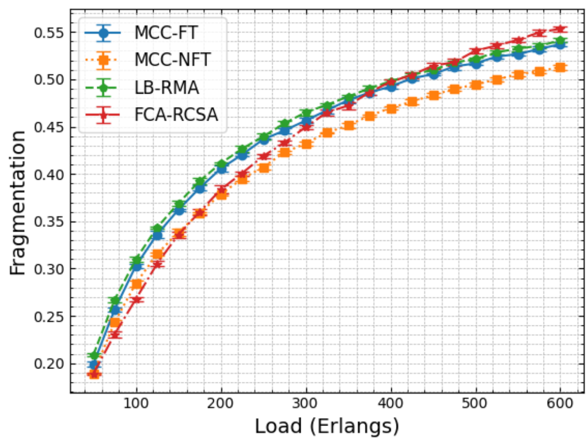


Figure 15. Fragmentation

average, 74% fewer requests than *FCA-RCSA*, and 17% less than *LB-RMA* in the same scenario.

As for *CpS*, shown in Figure 13, *MCC-FT* managed to outperform *LB-RMA* and *FCA-RCSA* by 40% over the load interval tested, and up to 60% at lower, 50E to 300E loads. *MCC-NFT* outperformed *LB-RMA* and *FCA-RCSA* by at least 36%, up to 58% at lower loads (50E-300E).

The average *Crosstalk* for the network, described in Figure 14, shows that *MCC-FT* reduced this metric by 43%, on average, compared to *FCA-RCSA*, up to 82% for loads of 50 to 200E. It also performed 50% better in comparison to *LB-RMA* for loads up to 125E. *MCC-NFT* reduced this metric in 37% compared to *FCA-RCSA*, peaking at a 60% reduction for loads of up to 250E. Compared to *LB-RMA*, *MCC-NFT* performed worst overall, but managed a reduction of 66% for loads of up to 75E.

MCC-FT fragmentation numbers, illustrated in Figure 15, are consistently ± *2%* of *FCA-RCSA* and *LB-RMA*'s numbers, respectively. *MCC-NFT* reduced fragmentation, on average, by 7% compared to *LB-RMA* and 3% up to 6% for medium loads (325E-600E) compared to *FCA-RCSA*.

Figures 16, 17, 18 and 19 refer to the network performance for the proposed multi-criteria routing approach in the NSF Topology. Figure 16 shows the BBR for this topology, where *MCC-FT* blocked, on average, 76% less bandwidth than *FCA-RCSA*, and 26% less than *LB-RMA*. *MCC-FT* reduced blocking in 67%, up to 81%, when only lower loads are considered (50E-400E), and although performed, on aver-

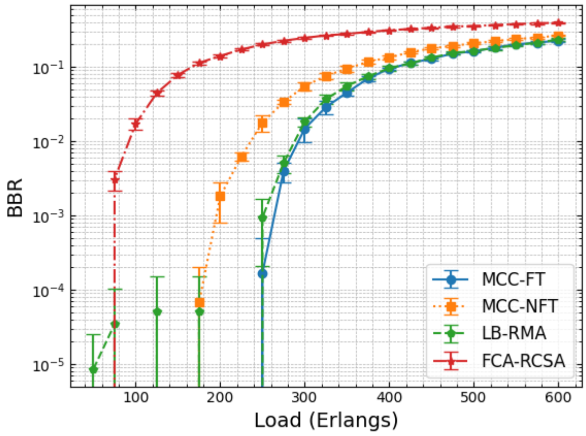


Figure 16. Bandwidth Blocking Ratio

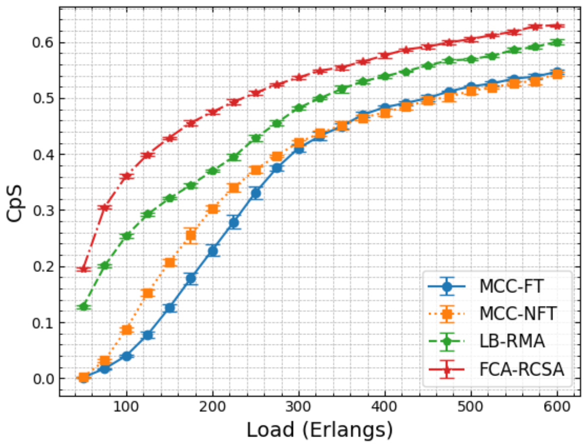


Figure 17. Crosstalk per Slot Ratio

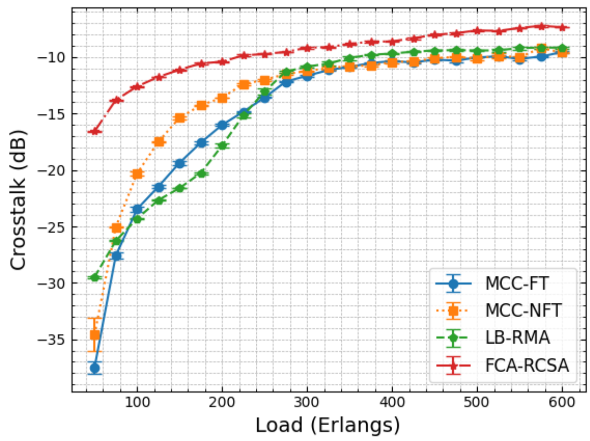


Figure 18. Average Crosstalk (DB)

age, worse than *LB-RMA*, it started blocking requests much later, at 150E, while *LB-RMA* started blocking requests at 50E.

Our *CpS* numbers from Figure 17, show *MCC-FT* reducing *CpS* in 38% and 31% compared to *FCA-RCSA* and *LB-RMA*, respectively. *MCC-NFT* managed a reduction in 32%, up to 50% for lower loads (50E-300E) compared to *FCA-RCSA*, and a reduction of 25%, up to 39%, again at lower loads, compared to *LB-RMA*.

The average *Crosstalk* for the network, shown in Figure 18, reveals that *MCC-FT* reduced crosstalk by 57% compared to *FCA-RCSA* in the interval tested, and up to 30%

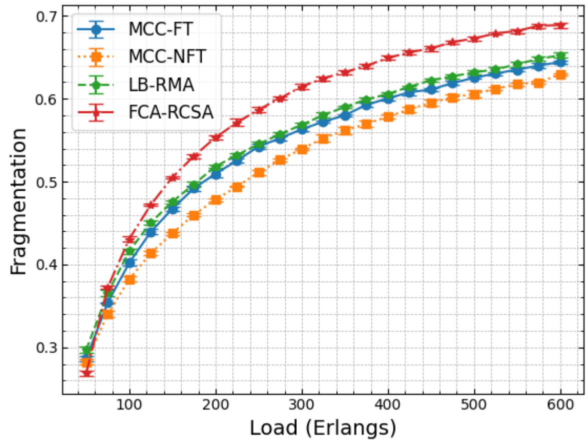


Figure 19. Fragmentation

compared to *LB-RMA* at lower loads of 50E to 100E. *MCC-NFT* managed to reduce this metric in 50% compared to *FCA-RCSA*, up to 70% at 50E to 225E loads, and reduced this metric by 16% compared to *LB-RMA* at higher, 350E to 550E loads.

The fragmentation statistics illustrated in Figure 19 show *MCC-FT*'s performance to be 7% better, on average, compared to *FCA-RCSA* and 2% better, compared to *LB-RMA*. *MCC-NFT* managed to reduce fragmentation by 11%, on average, compared to *FCA-RCSA*, and 6% compared to *LB-RMA*.

5.5 Discussion

In this section, we thoroughly analyze the correlation between the proposed approach's multi-criteria routing mechanism and its precise crosstalk-aware free spectrum mapping with the experimental results obtained for the topologies tested.

For the *USA* topology, illustrated in Figure 11(a), our results show that even with the flexible topology mechanism turned off (*MCC-NFT* curve), our precise crosstalk-aware free spectrum mapping managed to delay request blocking until 150E, which is three times better than the remaining benchmark algorithms. Once blocking started, it was still comparatively much lower. Additionally, we demonstrate that multi-criteria approaches for routing (*MCC-FT*) can outperform single-criterion approaches, such as *LB-RMA*, as well as approaches that sequentially (as opposed to simultaneously) apply more than one criterion for routing, such as *FCA-RCSA*, that ranks pre-processed k-shortest paths according to their fragmentation coefficient. By not entirely dismissing distance as a parameter for least-cost path decision it was also possible to avoid the atypical behavior of the *LB-RMA* approach where BBR might start higher at lower loads, later going down only to rise again along with the overall spectrum occupancy.

Regarding CpS, which measures the overlap between light-paths allocated to neighboring cores, and is directly linked to request blocks caused by exceeding the *XT-threshold* for a given modulation format, our approach managed to balance load in such a manner as to considerably reduce this metric. This means a reduction in allocation to adjacent cores, which consequently raises success rates for the allocation of light-paths that adopt highly efficient modulation formats with low tolerance to crosstalk, reducing also the need for spectrum resources, as seen in Table 4. Therefore, spectrum resources are used more efficiently. Our average crosstalk performance corroborates the aforementioned assessment, showing a network which is much less burdened with crosstalk at lower to intermediate loads, and even under stress maintains competitive performance.

Even though our multi-criteria, flexible-topology approach generates slightly more spectrum fragmentation than its static counterpart for this topology, it still performs competitively against our two benchmark approaches and even surpasses them at higher loads. Its non-flexible counterpart manages to reduce fragmentation consistently against both benchmark approaches.

In the case of the *NSF* topology, illustrated in Figure 11(b), our approach consistently outperformed the benchmark approaches in terms of *BBR* performance. This holds true even though the tested topology exhibits significantly different characteristics, including fewer and more distant nodes connected by a limited number of links. It was also possible to, once again, avoid the atypical behavior shown by *LB-RMA*, where, by disregarding the physical distance between nodes leads to highly inefficient candidate paths and ultimately causes bandwidth blocking even at very low loads. These results show that our approach's auto-balancing of spectrum occupation via flexibly changing the topology contributes in the reduction of crosstalk and fragmentation-related bandwidth blocking by utilizing network resources more efficiently.

Our *CpS* results reaffirm how our approach's auto-balancing of spectrum occupation via flexibly changing the topology contributes to less spectrum being allocated to adjacent-cores, consequently reducing *XT*-related bandwidth blocking even at relatively sparse networks, where path choices are reduced, and link-length limits modulation format selection. For the *NSF* topology, our average *Crosstalk* behaved similarly to the more dense *USA* topology, confirming that, even across very different topologies our approach behaved consistently, reducing the overall spectrum overlap across a wide range of loads.

Even though fragmentation showed the least reduction, our approach, with and without the use of the flexible topology mechanism, performed very competitively against our two benchmark algorithms and improved the overall network fragmentation.

The algorithms we used for comparison, although similar to ours in manners highlighted in Section 3, did not account, in their original testing, for scenarios as detailed as the ones considered in our research, where continuity and contiguity are adhered to, signal regeneration is not allowed and strict transmission reach and crosstalk thresholds are enforced for incoming and already established light-paths.

LB-RMA, in particular, suffers at lower loads for depending on spectrum occupancy for least-cost routing when, initially, occupancy is zero for every link, which inevitably leads to unusually inefficient paths being produced at first. As occupancy rises, this approach becomes more efficient at routing and eventually competes with what we proposed in this research. *FCA-RCSA* depends on a novel fragmentation metric to rank least-cost, distance-based paths, as well as to rank candidate cores within those paths, and prioritizes the path-core pair with the least fragmentation for allocation. This strategy is successful at reducing fragmentation over lower to medium loads, but the overall trade-off between this metric and request-blocking was less than adequate.

The results above shows how our approach outperforms algorithms from the literature across a wide load range within drastically different topologies while avoiding erratic behavior that might impair network performance even at lower loads when continuity and contiguity constraints are followed, and strict transmission-reach limitations and crosstalk thresholds are enforced. Looking at the curves side-by-side, we can see that our approach manages to allocate more resources (blocking less bandwidth) by doing so more efficiently, that is, with a more favorable quotient of overshadowed frequency slots to the total number of allocated slots (lower *CpS*), which in turn translates into the average network crosstalk starting at much lower values for our approach in comparison to the benchmark algorithms.

6 Conclusion

In this article, we presented a Multi-Criteria Crosstalk-Aware Flexible Topology *MCC-FT* strategy for SDM-EONs that dynamically adjusts the network topology in response to each incoming request and provides a free-spectrum map that accounts for the effects of crosstalk for both the incoming request and the already established light-paths, ensuring optimal performance under varying network conditions. Our approach enhances traditional routing methods by replacing static physical distances between nodes with a composite link-weight that combines both physical distance and current spectrum occupation. This allows the network to dynamically modify the topology before applying a least-cost algorithm to select candidate paths, resulting in more efficient routing decisions.

Through extensive simulations in networks constrained by transmission reach and inter-core crosstalk thresholds, our method consistently outperformed existing approaches from the literature in key metrics such as blocking probability reduction (BBR) and crosstalk per slot (CpS) and fragmentation, indicating efficient resource utilization. These results demonstrate the robustness and effectiveness of our routing method in balancing performance, reliability, and resource management in SDM-EONs, making it a promising solution for future high-capacity optical networks.

Despite very positive comparative results, the implementation of our approach also revealed challenges and limitations that show potential for future improvement. One key area involves incorporating additional network metrics, such as energy efficiency, into the multi-criteria decision-making process, which would provide a more comprehensive evaluation of network performance. Another challenge lies in addressing the trade-off between the efficiency of modulation formats and their sensitivity to crosstalk, requiring novel strategies to optimize this balance. Finally, the lack of differentiation between service classes within the current model presents a limitation, as integrating service-class-based decision-making could better reflect real-world network scenarios and improve resource allocation strategies.

For future work, we aim to extend our research by developing a reinforcement learning-based RMSSA approach trained on multiple topologies, as well several network configurations, so as to achieve a decision agent capable of making adaptive routing policies and modulation selection strategies by autonomously deciding on the relative importance of various network metrics in order to achieve the greatest long-term reduction in service-denial. It will include in its training more criteria, such as network performance and impairment metrics, in order to better align with current network configurations. Additionally, we plan to investigate core and spectrum allocation strategies tailored to diverse topologies, further enhancing the adaptability and efficiency of SDM-EONs under dynamic network conditions.

Declarations

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Authors' Contributions

Each author made substantial contributions to the conception and design of the study, as well as to the analysis and interpretation of data. Additionally, all authors were actively involved in drafting and critically reviewing the article, and they approved the final manuscript

Competing interests

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

Data can be made available upon request.

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