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Request Handling in Elastic Optical Data Center Networks: A Routing Algorithm Approach

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Abstract In recent years, worldwide communication has seen significant advancements driven by the growing demands of modern applications. These developments have introduced new requirements for data transfer, emphasizing the need for both high speeds and high efficiency. The cloud services model illustrates this shift, underscoring the importance of developing new mechanisms to handle increased data traffic. Beyond technological techniques, progress in the physical layer of networks is also crucial. It includes adopting spectrally and spatially flexible links that can precisely tune to the varying demands of network requests. In response to these challenges, this article proposes a routing algorithm tailored for Space-Division Multiplexing Data Center Elastic Optical Networks SDM-DC-EONs. The main objective of this algorithm is to improve network performance by maximizing the number of requests served efficiently. By taking advantage of the flexibility of optical networks, the proposed solution aims to enhance journal center capabilities while meeting the stringent requirements of modern communication systems. The potential of the proposed algorithm is seen in the Bandwidth Blocking Ratio, where it has better results than the other algorithms compared by up to two orders of magnitude, thus supporting the demands of the network.

Keywords: Data Center, Elastic Optical Networks, Routing, Space Division Multiplexing.

1 Introduction

Global communication has experienced a significant transformation in recent years, driven by the rapid growth of internet usage. The proliferation of video streaming, the expansion of digital services, Internet of Things (IoT) devices, and 5G technology has further accelerated this growth. This evolution has created new demands that traditional communication infrastructures struggle to meet [Panayiotou et al., 2023]. The volume of data transmissions pushes the existing networks to their limits. The demand for high-speed and high-capacity data transfer, necessary for activities like content streaming and real-time interactive applications, has emphasized the need for innovative solutions [Hosseini et al., 2024]. It creates a new challenge for service providers since these solutions must enhance network capacity to support the evolving digital communication landscape to prevent congestion and maintain high performance.

One prominent example of these emerging requirements is the cloud services model. It fundamentally transforms how data is stored, processed, and accessed. Cloud Computing enables vast applications, ranging from primary data storage to complex, real-time analytics and data transfer across global networks [Liu et al., 2023]. This model exemplifies the critical need for innovative mechanisms to manage the immense speed and volume of data that modern communication demands. New cloud applications intensify the pressure on communication networks to deliver reliable, fast, and efficient data transmission. The demand for robust and scalable network infrastructures continues to grow, noting advancements in data handling technologies and a rethinking of how networks are designed and managed to ensure they can keep pace with the growing demands [Aida and Uenohara, 2024].

The traditional communication network infrastructure, characterized by its fixed spectral, increasingly falls short of addressing the new demands posed by modern digital communication. As data volumes surge and application complexities grow, the limitations of these static networks become more apparent, revealing a critical need for a more adaptive approach to network management and data transmission. This is where the elasticity concept is explored, which provides an architecture with spectrally flexible links that become vital when allocating new demands [Sudhakar et al., 2024]. Conventional fixed-grid links rarely match the bandwidth required for new demands, causing more spectrum usage than is necessary, leading to underutilization of the network and potential loss of resources. On the other hand, spectrally flexible links, also called elastic links, can dynamically adjust their parameters to optimize performance based on the specific requirements of each request. This power of adaptability allows the network to perform fine-tuning, enabling more efficient use of available spectrum and enhanced overall network performance. The difficulties of implementing the Elastic Optical Networks model exist, however, we would point out that network traffic is approaching the limit of physical transmission capacity. In this sense, Elastic Optical Networks (EONs) are highly scalable, making them more suitable for accommodating future traffic, i.e. the proposal aims to reduce costs in the long term. To solve allocation in this network model there are routing and spectrum allocation (RSA) algorithms, which are able to find paths and define the set of slots needed for communication.

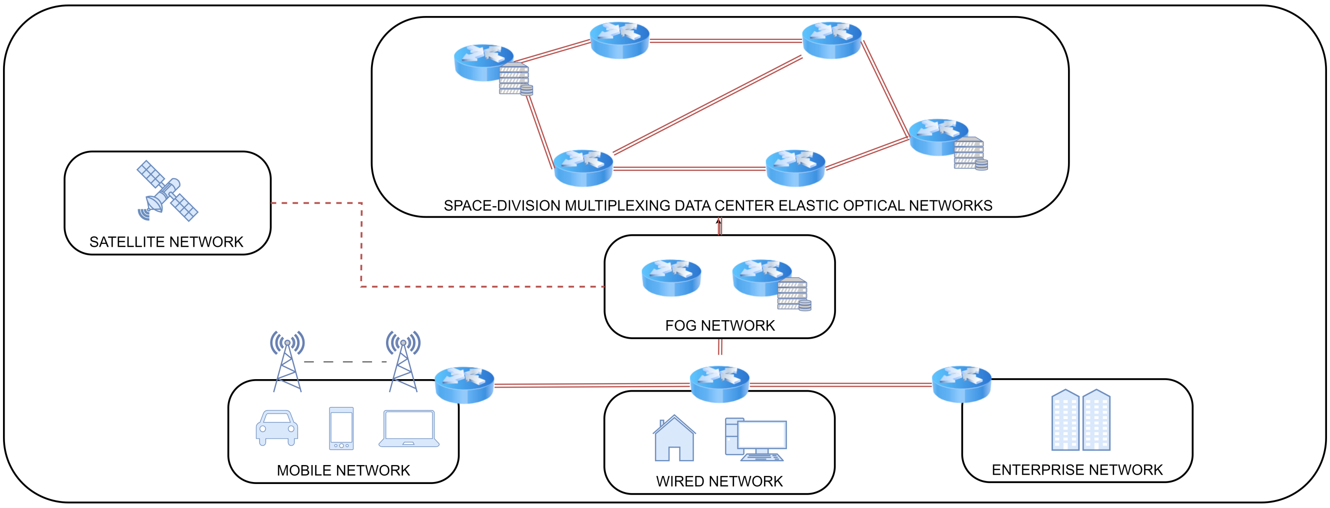


Figure 1. Layers from the outermost network to the Space-Division Multiplexing Data Center Elastic Optical Networks architecture.

In addition to the need for flexible links, improving the network's physical layer is essential for enhancing communication networks' overall performance and reliability. This area's advancement can lead to substantial speed, capacity, and resilience gains. By integrating spectrally and spatially flexible links into the physical layer, networks can dynamically adjust to the fluctuating demands of different applications and expand the total transmission capacity between two points in the network by adding a spatial dimension [Behera et al., 2023]. This flexibility ensures that network resources are allocated more efficiently, optimizing data transmission and reducing bottlenecks. As the capacity of the network model increases, so does the complexity of resource allocation. This gives rise to routing, spectrum, and core allocation (RSCA) algorithms, which are capable of selecting the best set of resources for network requests.

In addition to routing and spectrum allocation issues, two problems arising from this network architecture should be noted: inter-core crosstalk and spectrum fragmentation [Rezaee et al., 2024; Hafezi and Ghaffarpour Rahbar, 2024]. Crosstalk occurs when two or more transmissions are made in the same time window, occupying the same frequency band on adjacent cores [Chen et al., 2023]. The interference that one transmission adds to the other can make communication impossible, given the impact level on the signal that must be decoded at the other point in the transmission, causing errors. Another point to note is the modulation level, which impacts the distance and the acceptable interference limit. Fragmentation, on the other hand, is caused in the network frequency spectrum by the constant allocation and release of resources [Khorasani et al., 2023]. Some frequency bands may become available but not enough to be allocated to new requests, causing this resource to become idle and underutilized.

1.1 Problem Statement

To meet these challenges, this article presents a novel routing, modulation level, spectrum, and core allocation (RMLSCA) algorithm specifically designed for Space-Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs), as seen in Figure 1. These networks represent a cutting-edge approach to data transmission, leveraging the elasticity of optical networks to provide high-capacity, high-speed communication channels [Ahmadi et al., 2024]. Some approaches separate two sides to the resource allocation problem for this network model, where the first deals with the choice of routes for the request, and the second deals with the spectrum core allocation problem. In terms of the second half of the problem, efficient allocation seeks to deal with the core fragmentation resulting from frequent allocations. In addition, checking for crosstalk is also an essential component of core selection, as improper selection compromises transmission.

The algorithms found in the literature address sectors of the problem in isolation, focusing on specific aspects such as routing and allocation policies. This approach fails to address the limitations inherent to data center elastic optical networks, where the high volume, dynamic demands and spectrum crosstalk and fragmentation are a challenge. One of the greatest limitations in these networks is the difficulty to allocate resources in a efficient way while maintaining low congestion in the network's core.

In data center elastic optical networks, traditional algorithms often struggle when allocating resources due to miss balancing the use of both core and edge nodes, leading to oversaturated links while peripheral ones remain underutilized. In addition, the dynamic traffic requires an algorithm that suits the lacks of pattern in network demands.

Our article proposes a more complete scenario, considering the needs imposed by the architecture of Elastic Optical Networks combined with Data Center Networks. The proposed algorithm aims to maximize the number of data requests successfully served. By efficiently managing the bandwidth distribution and other critical resources, the algorithm ensures that the network can handle large volumes of data traffic without compromising performance or reliability, making SDM-DC-EONs a powerful solution for modern data centers' dynamic and demanding environments

1.2 Contributions

This article presents several key contributions that address the growing demands of modern communication networks, specifically within the context of Space-Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs):

- **Novel Routing Algorithm**: We propose a routing algorithm designed specifically for SDM-DC-EONs. This algorithm leverages call acceptance through the appropriate choice of spectral and spatial resources for allocation, handling requests from one point in the network to another as requests to specific DC nodes. Thus, managing the best route so as not to overload specific nodes and making a spectrum adjustment with attention to fragmentation, adapting to variable traffic conditions, and interfacing with DCs and other heterogeneous network demands.
- **Maximization of Served Requests**: A primary objective of the proposed algorithm is to increase the number of data transfer requests that can be efficiently processed, thus improving overall network throughput and performance.
- **Adaptability to Modern Applications**: The algorithm is designed to meet the demands of modern, high-bandwidth applications, ensuring that communication systems can handle growing data volumes while maintaining low latency and high efficiency.
- **Scalability and Flexibility**: Our approach demonstrates the ability to scale with increasing network demands and exhibits flexibility in resource allocation, making it a robust solution for future data center networks.

By addressing these areas, the proposed solution significantly advances the state of SDM-DC-EONs, contributing to more efficient, scalable, and adaptable network infrastructures.

1.3 Methodology

This work presents a routing algorithm for Space-Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs). The methodology adopted is structured around maximizing the number of network requests served while maintaining the high-efficiency use of network resources.

The core of our proposed solution is an algorithm that dynamically allocates spectral and spatial resources according to the specific demands of incoming network requests. This approach leverages optical networks' flexibility to ensure high data throughput and resource efficiency. Below, we outline the critical components of our methodology:

- **Network Model:** We model the SDM-DC-EONs as a graph where specially selected nodes represent data center components and edges represent optical links capable of supporting elastic bandwidth allocation. Each link can be divided both spectrally and spatially to accommodate different requests.
- **Traffic Characterization:** The incoming requests are characterized by their bandwidth requirements, spatial diversity, and latency constraints. The algorithm processes these requests in real-time, adjusting spectral and spatial resources accordingly.
- **Routing, Spectrum, and Core Allocation (RSCA)**: The proposed algorithm follows a Routing and Spectrum Allocation framework, where the shortest paths are initially computed, followed by spectrum assignment. The algorithm optimizes spectrum usage across multiple spatial dimensions to accommodate as many requests as possible without resource wastage.
- **Optimization Strategy:** The optimization strategy focuses on minimizing fragmentation in spectral and spatial resources, which helps increase the network's overall capacity. Additionally, we incorporate mechanisms to handle dynamic changes in network conditions, such as varying traffic loads and sudden increases in demand.
- **Performance Metrics:** We evaluate the effectiveness of our algorithm using key performance metrics, including blocking probability, spectrum efficiency, and overall network throughput. Simulations are conducted under varying traffic conditions to assess the algorithm's robustness and adaptability.

First, we adapted the elastic optical network to have data center nodes. In addition, we modeled the traffic for this new network model, offering support in the simulation tool. We propose a new algorithm responsible for allocating resources in SDM-DC-EONs. We seek to maximize the number of requests served by the network, boosting total capacity by allocating resources more fairly. Finally, we evaluate the proposed algorithm against others in the literature. By structuring the methodology around these principles, the proposed solution addresses the unique challenges of SDM-DC-EONs and offers a scalable approach for improving data center network performance.

1.4 Organization of this Article

This article is organized as follows. Section 2 outlines the state-of-the-art spectrally and spatially flexible grid architectures and Data Center Elastic Optical Networks. Section 3 describes the Redeclare Algorithm. Section 4 discusses the simulation and the results obtained. Finally, Section 5 presents the conclusion.

2 Related Works

In recent years, advances in cloud services and network technologies have required the development of new mechanisms to manage the increasing speed and volume of data traffic. Studies have explored various approaches to improving the performance of Elastic Optical Networks, such as exploiting the spatial dimension with the SDM-EONs architecture and using it in the Space-Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs).

To support data exchange in SDM-EONs, Hosseini et al. [2024] proposed a novel dynamic multipath routing algorithm to reduce blocking probability bandwidth and energy consumed by Bandwidth Variable Transponders (BVTs). They used multiple lightpaths but the same set of fibers, ensuring the differential delay does not become a problem. The effectiveness of the modulation format is tested, and the intercore crosstalk restrictions are considered. Despite dealing with data flow in the SDM-EONs architecture, the work does not consider data center elements in the network.

Machine learning techniques are also an option for resource management. Asiri and Wang [2024] applied Deep Reinforcement Learning for Quality of Transmission-aware (QoT-Aware) when routing flows at Elastic Optical Networks. The agent learns from Routing, Modulation, and Spectrum Assignment (RMSA) policies and evolves to make a decision that utilizes the maximum network spectrum. To evaluate the QoT, they consider other factors such as physical impairments, spectrum fragmentation, and traffic dynamics. The rewards guide the agent in finding a light path that meets the QoT requirements while achieving a lower blocking ratio with a high bit rate. The work does not include space division multiplexing as an element of network resource allocation. The core and spectrum allocation subproblem present in our work has its parallel in a simplified form in this work in the literature, considering the spectrum of only one core for adjusting requests. It also does not take into account the data center streaming scenario.

Agarwal and Bhatia [2024] proposed a meta-heuristic approach for Routing, Modulation, and Spectrum Allocation using Genetic Algorithm (GA). They compared the effectiveness of single-path and multi-path routing, taking into account the blocking probability for the networks simulated. The proposed algorithm provides the most optimal solution. The authors do not consider data center elements and also do not consider the network to be spatially flexible, i.e., intrinsic problems such as intercore crosstalk are not addressed, thus reducing the complexity of resource allocation in a network link.

Villamayor-Paredes et al. [2023] approached a subset of a problem, the RMLSA. They proposed two approaches to the problem based on Genetic Algorithm (GA) that allows permutating the routes.The algorithm calculates the path and selects the appropriate modulation format and set of resources for the lightpath, aiming to minimize the maximum frequency slot rate used and the blocking ratio for dynamic traffic. The algorithm uses the GA to allocate resources but does not consider the spatial dimension, which reduces the problem since it allocates requests to a single core. The willing scenario does not use nodes as a data center; it considers all nodes homogeneous.

Chen et al. [2023] address the resource allocation problem in SDM-EONs, presenting a parameterization strategy to indicate the spectrum sensitivity (SS) in a matrix concerning core crosstalk. They propose an ILP model that uses the crosstalk-sensitive constraint to optimize spectrum efficiency. In addition, they propose three heuristics focusing on core allocation coupled with SS, which have been shown to achieve the best trade-off between average crosstalk and spectrum efficiency when compared to each other in static and dynamic network scenarios. Although the work considers the SDM architecture and addresses the challenges of network allocation, data center flows are not treated differently in the allocation.

In order to utilize the high flexibility of the network and prevent one of the biggest challenges, which is bandwidth fragmentation, Khorasani et al. [2023] introduce a new spectrum allocation policy for EONs called Smart-Fit, which searches for spaces that are exactly the size of the request and stores them so that the proposed best-fit calculation can be performed. In addition, a multipath routing algorithm per core is proposed, showing high scalability and fragmentation reduction results and reduced transponder usage. Combining the two proposals also proves to be effective in reducing spectrum waste and fragmentation. The multipath/multicore allocation policy deals with fragmentation but does not deal with the data center scenario.

Following the critical problem of fragmentation in EONs, Hafezi and Ghaffarpour Rahbar [2024] propose two new algorithms that aim to reduce the problem of fragmentation and reduce network blocking. One of the algorithms prioritizes the frequency range, while the other prioritizes core selection. The demands of the proposed scenario have three priority levels met in the network, and resources are allocated. Only the RMSA problem is addressed, disregarding the spatial dimension and data center networks.

Rezaee et al. [2024] proposed a crosstalk-aware routing algorithm, a fundamental problem when using Multicore Fibers (MCF), so two policies are defined based on the calculated crosstalk levels. In addition, they propose a new approach to resource allocation with crosstalk-aware bandwidth slicing, which, in addition to dealing with crosstalk, can allocate demands that have a greater need for bandwidth since, after slicing, they can be slotted into new regions, reducing fragmentation. The work does not consider Data Center Networks for routing and handling flows.

The algorithm proposed by Zou et al. [2024] takes care of disasters that can occur in the network, proposing a recovery algorithm that restores the set of Virtual Network Functions (NFV) called Service Function Chain (SFC), which is a crucial challenge for data center elastic optical networks (DC-EONs). The fiber represented in this work is not multimode/multi-core, reducing the complexity of the allocation problem by not considering the spatial dimension and not focusing on reducing fragmentation.

The new demands for task offloading that emerging applications are generating motivates Chen et al. [2024]. The aim is to optimize network resource allocation and reduce end-to-end latency by deciding if|where to offload the user in a Cloud-Edge Elastic Optical Networks (CE-EONs). They proposed an Integer Linear Programming (ILP) model as an initial solution and several heuristics to cope with partial resource offloading. They highlight the Proportional Segment Approach's effectiveness in achieving the lowest E2E latency, low blocking probability, and optimized network resource allocation in dynamic scenarios.

While the works mentioned above and found in the literature address challenges in elastic optical networks, they often tackle these issues by dividing them into smaller, isolated problems. Notably, the core allocation problem tends to be overlooked in studies where the optical fiber is assumed to have only a single core. In contrast, our proposal offers a comprehensive solution that integrates routing, allocation, and request handling in Data Center Networks combined with Space Division Multiplexing Elastic Optical Networks, providing a more complete approach to addressing the complexities of these systems.

3 Redeclare Algorithm

This section introduces the Routing, Modulation Level, Spectrum, and Core Allocation for SDM-DC-EONs (Redeclare) Algorithm. This algorithm establishes connections when sufficient network resources are available for successful transmission from one point to another. Data centers are positioned in network nodes, which handle specific requests according to the network's traffic generation. In addition, six different modulation levels are applied, considering the total transmission distance in km between the nodes. In our proposal, the route is first found, and then cores and slots are allocated to fulfill the request to ensure continuity and contiguity constraints.

3.1 Network Overview

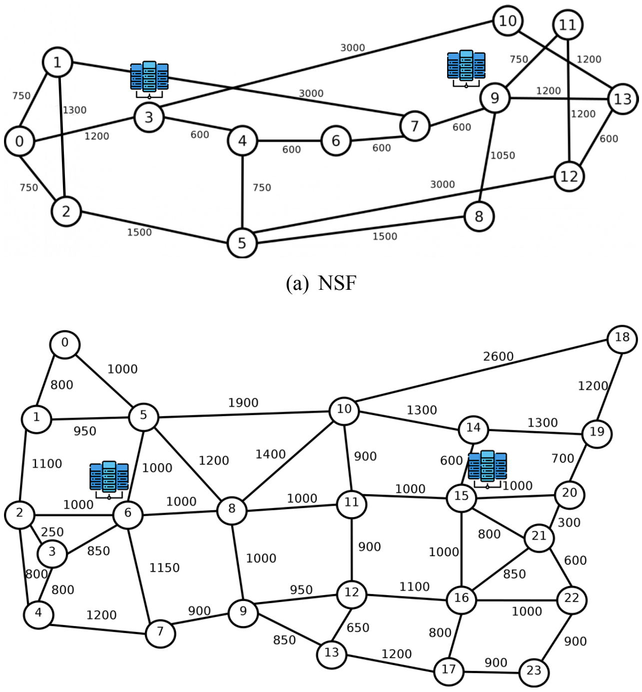
The optical network operates with Spatially Flexible Reconfigurable Optical Add/Drop Multiplexers that allow wavelength-selective switch and space-wavelength granularity with Multiple-Input Multiple-Output (MIMO) transceivers. In this way, the entire network operates through EONs, without the need to transition to other optical network architectures, i.e. the entire backbone has technology that supports this type of communication. However, the ability of these networks to be managed in a more refined way in terms of resource allocation means that the effectiveness of the network is higher, with little waste of resources.

The network comprises Multi-Core Fibers (MCF) links with seven cores arranged in a hexagonal array, each with a spectrum availability of 320 frequency slots with 12.5 GHz each. A pair of nodes with one bidirectional link is used, and the link length varies according to the distances in km. The network equipment does not allow the exchange of circuits between different cores, being necessary to maintain the restriction of core continuity. Besides that, the number of slots necessary to satisfy the bandwidth demands depends on the modulation level chosen. Paths are separated by a Filter Guard Band (FGB) represented by one slot.

We consider modulation levels present in Table 1 for path allocation. However, the connection Quality of Transmission (QoT) depends directly on the transmission distance and modulation level chosen since the modulation level adopted must consider the distance between source and destination. Also, modulation has restrictions on the interference that one transmission causes to the other, so crosstalk is evaluated and must remain below the limit in order to be decoded at the other end of the communication. In this context, the most efficient modulation level is selected so that the path length does not compromise the transmission capacity. The topologies were selected because they are important global communication channels and also because of the difference in the layout of the nodes and links, number of connections and distance between nodes

3.2 Operations

The Redeclare is an RLMSCA algorithm for SDM-DC-EONs that can be employed for different loads, scenarios, and topologies. The algorithm aims to reduce the number of blocked requests and increase the amount of data transmitted over the network.



(a) NSF

(b) USA

Figure 2. Topologies and network model.

Table 1. Modulation Level

Notation	Distance (Km)	Capacity (Gbps)
BPSK	4,000	12.5
QPSK	2,000	25
8QAM	1,000	37.5
16QAM	500	50
32QAM	250	62.5
64QAM	125	75

The algorithm 1 describes the sequence of operations. The algorithm's input is the set of information about the network, consisting of Vertices, Links, Cores, Slots and Requests. The expected output is the lightpath with sufficient resources to be allocated to each request, when available.

In Line 3, the topology is scanned and the links and cores are recognized. In Line 4, the data centers are placed, as in Figure 2, where k represents the number of data centers, where $k = 2$, as described in the article Ju et al. [2022]. There is a relaxation compared to the original proposition since it requires backup path in disaster scenario cases.

Naturally, there will be a flow concentration in these nodes that accommodate data centers, and the routing stage must maximize the accepted requests. In Line 5, all the requests from the set arriving on the network are received. For each request, Line 6 shows the 3-shortest path. For each of the paths found, Line 8 selects the modulation according to the path distance. In the core and slot matrix for all the links on the path, the available resources are checked, and the levels of crosstalk and fragmentation are measured to check that they are acceptable so as not to hinder transmission. At the end, on Line 19, the lightpath is returned with the core, slot and bandwidth required for the modulation applied

Table 2. Notation

Notation	**Definition**
src	Source node
dst	Destination node
b	Bandwidth required in Gbps
$e \in E$	Link from the network
$v \in V$	Node from the network
$C \in C$	Core from the network
$s \in S$	Slot from the network
$r(src, dst, b) \in R$	Request from src to dst with bandwidth demand of b
$m \in M$	The set of modulations $M = \{1, 2, 3, 4, 5, 6\}$
$p \in P$	Path for each request
lp	Lightpath
b_m	Number of slots required for transmission according to the modulation applied
f	Fragmentation
xt	Crosstalk

Algorithm 1 Redeclare

1: **Input:** V, E, C, S, R
2: **Output:** Lightpath for DC-Node connections
3: Read network topology V and E
4: $Datacenter\_positioning(k = 2)$
5: **for** all $r(src, dst, b) \in R$ **do**
6:     Find set P of paths
7:     **for** all $p \in P$ **do**
8:         Calculate modulation level $m \in M$
9:         according to the distance
10:         **for** all $c \in C$ **do**
11:             **for** all $s \in S$ **do**
12:                 **if** all $s + b_m$ slots are available **then**
13:                     Measurement of xt and f
14:                     Allocate (c, s)
15:                 **end if**
16:             **end for**
17:         **end for**
18:     **end for**
19:     **return** $lp(c, s, b_m)$
20: **end for**

The complexity of the Redeclare algorithm is analyzed as follows. The complexity of reading network topology is $O(V + E)$, where V is the set of vertices and E is the set of edges of the topology. To find the path we consider the Yen's algorithm that has the complexity of $O(KV(V + E)logV)$. The core/slot selection in the worst case is $L * C * S$, which means the allocation occurs at the last core C and last slot S for every link L. The complexity of the Redeclare is $O(KV(V + E)logV)$.

4 Performance Evaluation

This section presents the metrics evaluated in the work, their relevance, and proposed algorithm's results compared with two other algorithms in the literature.

The simulations were performed using the Flexgridsim simulator, specifically designed for Elastic Optical Networks and also supports Space Division Multiplexing, with adaptations for Data Center Networks [Moura and Drummond, 2025].The first algorithm [Ju et al., 2022] focuses on reducing blocking and fragmentation. However, it does not consider the network with Spatial Division Multiplexing. The second algorithm [Liu et al., 2022] focuses on serving requests that arrive in the network and are intrinsically linked to the network's data centers. This work does not consider network requests not connected to the data center.

4.1 Metrics

For performance evaluation of the proposed algorithm, we utilized the following metrics: Blocking Bandwidth Ratio (BBR), Average Bits per Second (AVGBPS), Crosstalk per Slot (CpS), Energy Efficiency (EE), Fragmentation Ratio (FR), Data Transmitted (DT), Mean Hops per Path (HP), and Power Consumption (PC).

$$BBR = \frac{\sum_{i=1}^{n} \alpha_i \cdot \mathrm{BW}_{\text{blocked}}(i)}{\sum_{j=1}^{m} \beta_j \cdot \mathrm{BW}_{\text{request}}(j)} \tag{1}$$

The *BBR* represents the ratio of blocked bandwidth to requested bandwidth in the network. In Equation 1, α_i refers to the number of times the bandwidth for request i was blocked, while β_j refers to the total number of requests for bandwidth j. $\mathrm{BW}_{\text{blocked}}(i)$ denotes the bandwidth blocked for request i, and $\mathrm{BW}_{\text{request}}(j)$ indicates the bandwidth requested for j. The sums are taken over all n blocked requests and all m total requests.

$$CpS = \frac{\sum_{i=1}^{n} \gamma_i \cdot (f_{\text{adj}}(i) + f_{\text{core}}(i))}{\sum_{j=1}^{m} \phi_j \cdot S_{\text{total}}(j)} \cdot T \tag{2}$$

The *CpS* measures the level of interference, or crosstalk, that occurs when multiple signals are transmitted in adjacent cores or slots within the same frequency band. In Equation 2, γ_i represents the interference caused by slots allocated in the same frequency spectrum for core i, while $f_{\text{adj}}(i)$ and $f_{\text{core}}(i)$ account for the interference factors of adjacent slots and cores, respectively. The denominator includes ϕ_j, the total number of slots used on link j, and $S_{\text{total}}(j)$, the total available slots on that link. The final term T represents the periodic time divisions used in the calculation.

$$EE = \frac{\sum_{i=1}^{n} \gamma_i \cdot \mathrm{BW}_{\text{accepted}}(i)}{\sum_{j=1}^{m} \epsilon_j \cdot (P_{\text{transponder}}(j) + P_{\text{switch}}(j) + P_{\text{amplifier}}(j))} \tag{3}$$

The *EE* evaluates how efficiently the network uses energy to transmit accepted data. In Equation 3, γ_i is the total bandwidth (in Mbps) of all accepted requests in the network, and ϵ_j represents the total energy consumed (in Joules) by network components, such as transponders, switches, and optical amplifiers, for link j. The terms $P_{\text{transponder}}(j)$, $P_{\text{switch}}(j)$, and $P_{\text{amplifier}}(j)$ describe the energy consumption for each of these components on link j, respectively.

$$FR = \frac{\max\left(\sum_{i=1}^{n} \mu_i \cdot \text{Slot}_{\text{available}}(i)\right)}{\sum_{j=1}^{m} \delta_j \cdot S_{\text{available}}(j)} \tag{4}$$

The *FR* quantifies how fragmented the available spectrum is within the network. In Equation 4, μ_i denotes the number of blocks of available slots in link i, and $\text{Slot}_{\text{available}}(i)$ is the number of available slots for a specific request i. The denominator contains δ_j, representing the total available slots on link j, and $S_{\text{available}}(j)$, the total available slots in the network for that link. This equation helps to measure inefficiencies caused by fragmentation in the network's frequency spectrum.

$$AVGBPS = \frac{\sum_{i=1}^{n} \text{BW}_{\text{transmitted}}(i)}{T_{\text{total}}} \tag{5}$$

The *AVGBPS* calculates the average bandwidth transmitted per second across all requests. In Equation 5, $\text{BW}_{\text{transmitted}}(i)$ represents the bandwidth successfully transmitted for request i, and T_{total} is the total time duration during which the bandwidth was measured.

$$DT = \sum_{i=1}^{n} \text{BW}_{\text{transmitted}}(i) \cdot T(i) \tag{6}$$

The *DT* represents the total data sent through the network. In Equation 6, $\text{BW}_{\text{transmitted}}(i)$ is the bandwidth transmitted for each request i, and $T(i)$ is the time duration for which that bandwidth was utilized.

$$HP = \frac{\sum_{i=1}^{n} H(i)}{n} \tag{7}$$

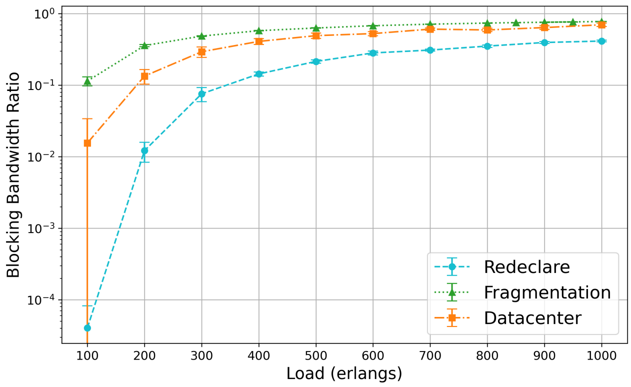
The *HP* measures the average number of hops (i.e., intermediate nodes) required for data to travel from source to destination across all requests. In Equation 7, $H(i)$ represents the number of hops for request i, and n is the total number of requests.

$$PC = \sum_{i=1}^{n} \left(P_{\text{transponder}}(i) + P_{\text{switch}}(i) + P_{\text{amplifier}}(i)\right) \tag{8}$$

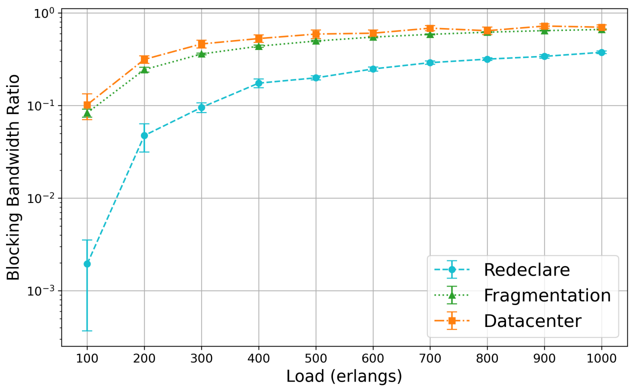
The *PC* calculates the total energy consumption of the network components, such as transponders, switches, and amplifiers, across all requests. In Equation 8, $P_{\text{transponder}}(i)$, $P_{\text{switch}}(i)$, and $P_{\text{amplifier}}(i)$ represent the power consumption for these components for each request i.

4.2 Results

The topologies that supported our simulations are the NSF Topology 2(a) and the USA Topology 2(b). The NSF Topology has 14 nodes and 20 links and presents few links that can communicate from east to west and vice versa, contributing to overload in link usage in the middle links. While USA Topology has 24 nodes and 43 links, it is very connected, allowing the routing to find many alternative paths, considering the algorithm's intention.



(a) NSF

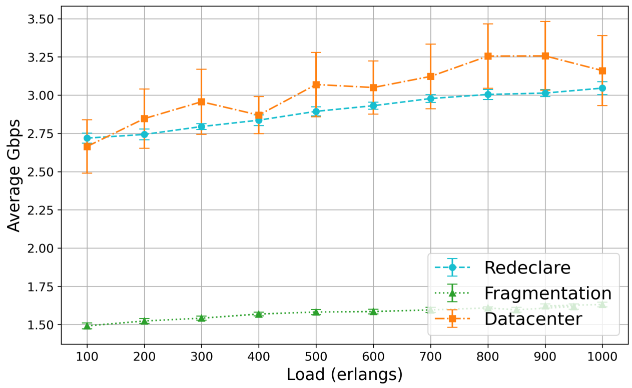


(b) USA

Figure 3. Blocking Bandwidth Ratio

Figure 3 shows the results for the bandwidth blocking ratio for the simulated topologies. For the NSF topology, the Redeclare algorithm has two orders of magnitude less blocking than the DataCenter algorithm and up to three orders of magnitude less blocking than the Fragmentation algorithm at lower Erlang loads. For all loads, the Redeclare algorithm had lower blocking, while the other two algorithms had higher blocking, coming close to each other for loads above 500 Erlang. The Redeclare algorithm showed less blocking for the USA topology than the compared algorithms by almost two orders of magnitude. The DataCenter and Fragmentation algorithms had similar results, although the DataCenter algorithm blocked more requests.

The Fragmentation algorithm considers the core fragmentation level as the main element of its resource allocation policy, while separating the routing phase as secondary in its proposal. This means that the chosen route may not be optimal in terms of distance, causing inefficient allocations when the network bandwidth blocking ratio is calculated. On the other hand, the DataCenter algorithm takes a different approach to resource allocation, since the traffic flow is concentrated on specific nodes. Although it is simple to identify the most used nodes, congestion is created in the center of the network which unbalances the use of resources, where some links saturate and others are underused over time. This situation not only restricts the available links, but also makes it difficult to allocate long-duration requests. In the end, this uneven utilization is detrimental to the performance and efficiency of the network. The Redeclare algorithm performs routing first, seeking to allocate the least amount of resources (since more links means more cores x slots). Then, within the smallest routes selected, it searches for the set with the least impact on network fragmentation and crosstalk.



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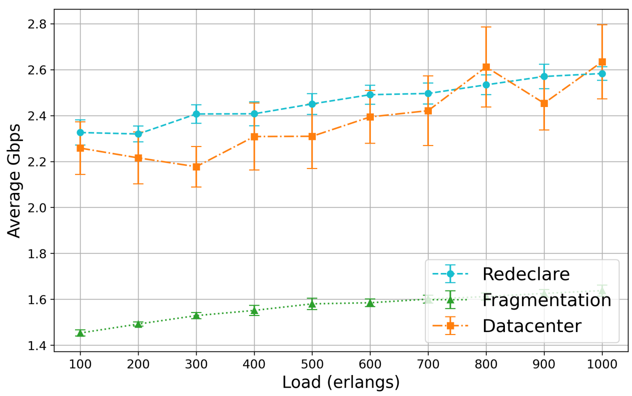

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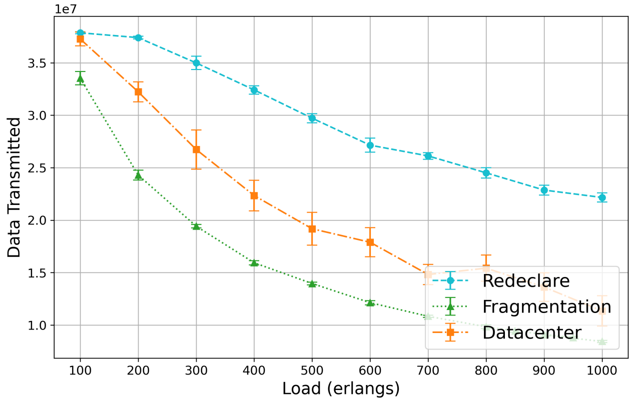
Figure 4. Average Gigabits per Second

Figure 4 shows the results for the average gigabits per second for the simulated topologies. For the NSF topology, the Redeclare algorithm has the second highest average Gbps, with values between 2.75 and 3. The DataCenter algorithm has an average Gbps between 2.5 and 3.25. The Fragmentation algorithm has an average close to 1.5 Gbps. For the USA topology, the Redeclare and DataCenter algorithms are also close, with Redeclare showing better results between 2.3 and 2.6 Gbps on average. The DataCenter algorithm shows average Gbps between 2.2 and 2.6. The Fragmentation algorithm averages between 1.4 and 1.6. The results are related to blocking and the use of modulation, with the Fragmentation algorithm showing greater blocking and therefore less data transmitted. The proposed Redeclare algorithm, on the other hand, has less blocking and transmits a large amount of data.

The average gbps metric is related to the network's blocking rate, along with the modulation applied to each transmission. As the Fragmentation algorithm considers second-stage routing, it possibly selects longer paths and applies modulation that supports longer distances, consequently lowering the transmission rate. While the other two algorithms adopt the policy of first finding the route and then allocating the spectrum resources.

Figure 5 shows the results for the data transmitted over the network for the simulated topologies. The Redeclare algorithm performs better on data transmitted over the network, as it blocks fewer requests. In the NSF and USA topologies, the result is similar, with a unit close to 2.5 units, two units more transmitted at higher loads than the algorithms compared, reflecting how the use of modulation increases network capacity. For the NSF topology, the DataCenter algorithm has the second lowest result with a result close to 1.3 in 1000 Erlang. The Fragmentation algorithm shows the worst result over the simulated loads. For the USA topology, the Fragmentation and DataCenter algorithms invert their results over the simulated loads but are similar at 1000 Erlang.



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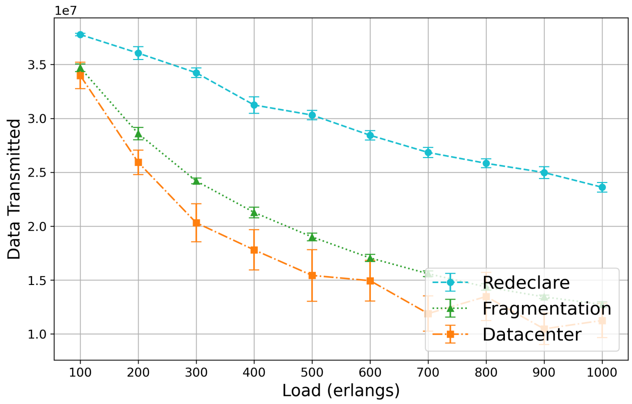

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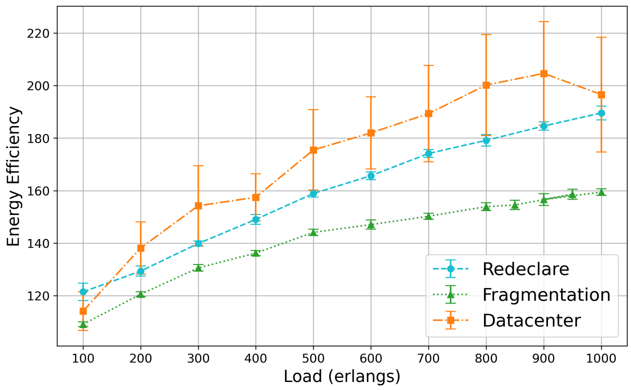
Figure 5. Data transmitted

The amount of data transmitted is related to the bandwidth blocking ratio, so the algorithms have equivalent curves, where the highest bandwidth blocking ratio has the lowest amount of data transmitted over the network.

Figure 6 shows the energy efficiency for both simulated topologies. The DataCenter algorithm has the highest efficiency, although it does not accept as many requests as the others, which means that although it rejects a lot of calls, it efficiently utilizes available resources, transmitting a substantial amount of data during limited time windows. The proposed algorithm shows results between the other two compared, with a higher energy efficiency than the Fragmentation algorithm, due to the lower number of rejected connections in the network, although the NSF topology does not allow modulations with a higher transfer rate to be applied many times because of the length of the links. The Fragmentation algorithm is less energy efficient because it allocates spectrum in such a way as to prioritize the reduction of frag-



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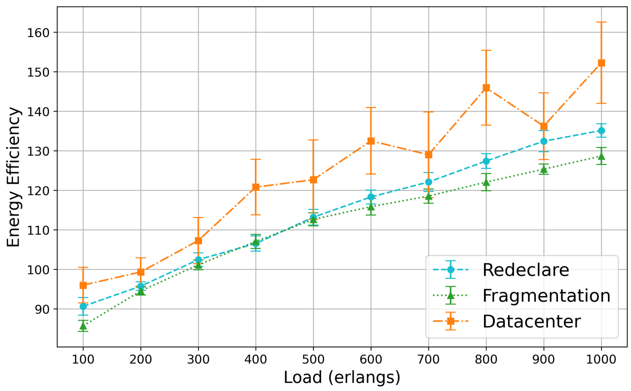

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Figure 6. Energy Efficiency

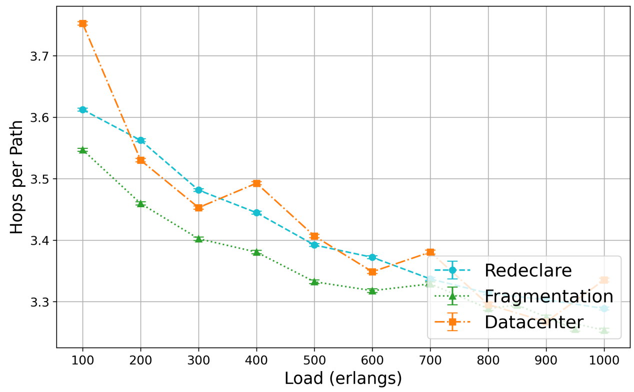
mentation, which can lead to the use of other link cores, increasing energy consumption.

Figure 7 shows the average hops per path. For the NSF topology, the average is very similar for the three algorithms around 3.6 for lower loads and 3.3 for high loads, which is due to the topology's characteristic of little connectivity and longer links. The USA topology, on the other hand, has a higher average number of jumps due to its greater connectivity. The Redeclare presents an average between 4.1 and 3.8 hops, similar to Fragmentation algorithm. A highlight is the DataCenter algorithm, which, due to the possibility of communicating with more distant or closer data centers, has a variation in the average number of hops.

Redeclare algorithm is more insistent when allocating the route, so it allows larger paths to be allocated if smaller ones are unavailable, causing the average number of jumps to increase.

Figure 8 shows the power consumption results of the simulated algorithms. The proposed algorithm has the highest consumption compared to the other algorithms, since it also blocks the fewest requests coming into the network and transmits the most data, so it is expected that consumption will be higher to support transmissions. Meanwhile, for the NSF topology, the DataCenter algorithm consumes more energy than the Fragmentation algorithm, and the situation is reversed for the USA topology. This behavior is similar to the amount of data transmitted, i.e. the power consumption ratio is directly related to the data transmitted by the network.

Figure 9 shows the results for Crosstalk per Slot. The Proposed algorithm has higher Crosstalk per Slot because it al-



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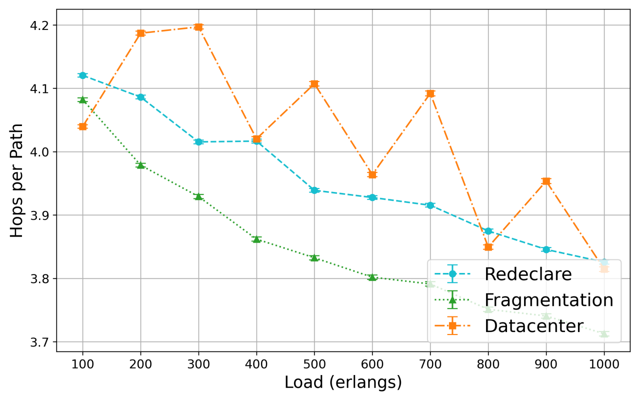

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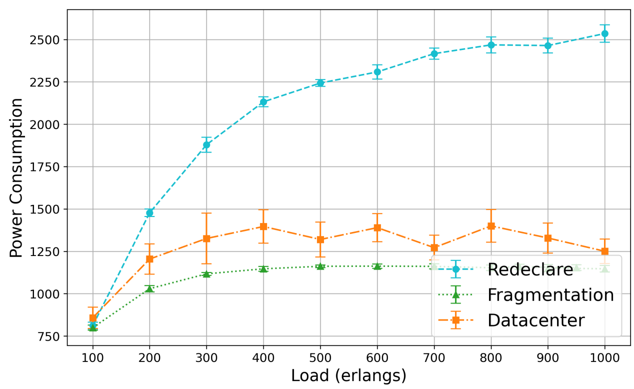
Figure 7. Hops per path



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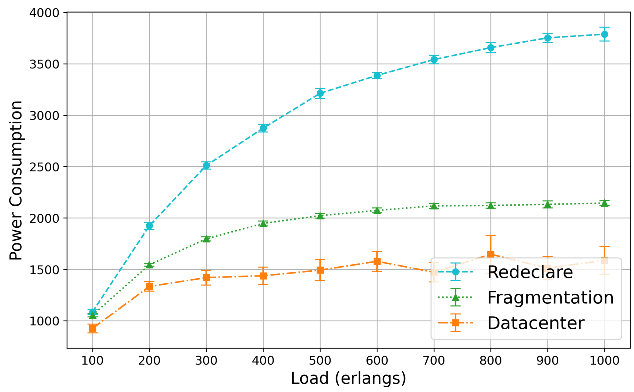

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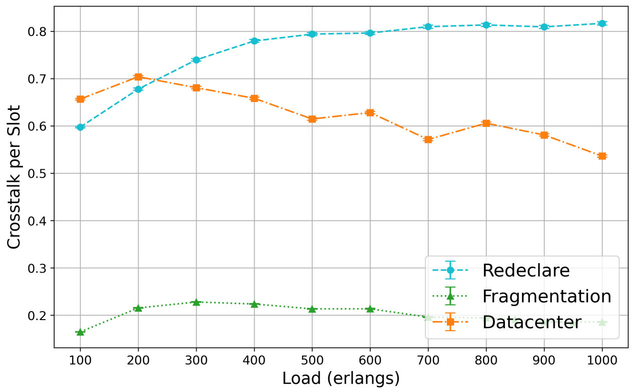
Figure 8. Power Consumption



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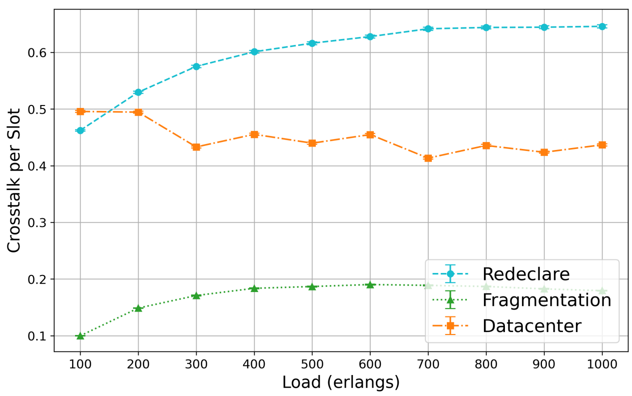

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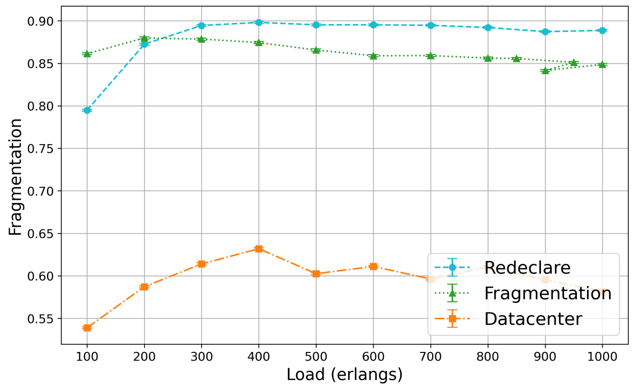
Figure 9. Crosstalk per Slot



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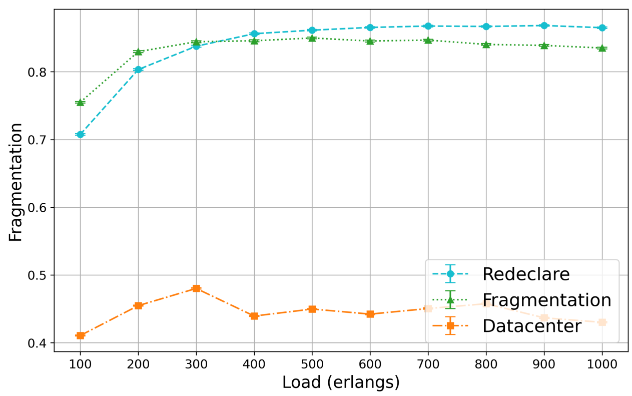

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Figure 10. Fragmentation

locates more resources and handles more requests, i.e. more cores are active for communication. Meanwhile, Fragmentation has allocation policies that prioritize non-adjacent cores, reducing crosstalk, as well as not handling as many requests as the proposed algorithm. As for the DataCenter algorithm, it has high crosstalk per slot, but it doesn't handle as many requests, and there are no policies for such optimized allocation.

As a problem arising from the allocation and removal of transmissions, algorithms that make more connections usually have a higher average crosstalk value. Meanwhile, the Fragmentation algorithm's strategy tends to mitigate crosstalk both by policy and by not accepting so many requests. The same goes for DataCenter algorithm, which may have a higher concentration of calls in specific regions but blocks other requests, directly affecting crosstalk.

5 Conclusions

In this article, we propose an algorithm that allocates resources to the most significant number of requests with a low impact on communications between data centers. We analyze the interference of transfers between two data center points on other network requests.

The combination of technologies that make up the SDM architecture is recent, and most of the studies in the literature deal with isolated parts of the resource allocation problem specific to this network model. The problems are subdivided into routing, core and spectrum allocation, and data center flow management. Our approach proposes a more complete scenario, with a broader view of network flows, both communication between common network nodes and data transmission to data center nodes. Therefore, the algorithm can handle communication and allocate the necessary resources to handle as many calls as possible while there is availability in the network.

The work is directed towards a more complete approach to elements and performance metrics specific to Data Centers, that is, developing the architecture addressed. Furthermore, resource allocation can be done through more robust strategies and machine learning techniques. There is also scope for survival strategies in disaster scenarios and deeper analysis of communication between DCs, more specifically, and their impact on other requests in the optical environment.

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Authors' Contributions

Each author declares substantial contributions through the conception and design of the study, as well as the analysis and interpretation of data. Additionally, each author contributed significantly to the drafting and critical review of the the article.

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.

References

Agarwal, R. and Bhatia, R. (2024). Multipath routing using genetic algorithm in elastic optical network. *Journal of Optics*, 53(3):2316–2321.

Ahmadi, M., Hadi, M., and Reza Pakravan, M. (2024). Power-efficient joint dynamic resource allocation in virtualized inter-data center elastic optical networks. *IEEE Access*, 12:75599–75609.

Aida, H. and Uenohara, H. (2024). Low-latency optical switching technology for next-generation edge-cloud computing platforms. *Opt. Continuum*, 3(6):970–982.

Asiri, A. and Wang, B. (2024). Deep reinforcement learning for qot-aware routing, modulation, and spectrum assignment in elastic optical networks. *Journal of Lightwave Technology*, pages 1–27.

Behera, S., Savva, G., Manousakis, K., and Ellinas, G. (2023). Impairment-aware routing, modulation, spectrum, and core allocation with bit loading in spectrally–spatially flexible optical networks. *J. Opt. Commun. Netw.*, 15(6):318–332.

Chen, B., Lei, Y., Hu, J., Liu, L., Ma, W., Wu, J., Gao, M., Shao, W., and Ho, P.-H. (2023). Crosstalk-sensitive core and spectrum assignment in mcf-based sdm-eons. *IEEE Transactions on Communications*, 71(12):7133–7148.

Chen, B., Liu, L., Fan, Y., Shao, W., Gao, M., Chen, H., Ju, W., Ho, P.-H., Jue, J. P., and Shen, G. (2024). Low-latency partial resource offloading in cloud-edge elastic optical networks. *J. Opt. Commun. Netw.*, 16(2):142–158.

Hafezi, M. and Ghaffarpour Rahbar, A. (2024). Fragmentation-aware with core classification algorithms for spectrum allocation in elastic optical networks-space division multiplexing (sdm-eon). *Optical Fiber Technology*, 82:103622.

Hosseini, S., de Miguel, I., Merayo, N., de la Rosa, R., Lorenzo, R. M., and Durán Barroso, R. J. (2024). Energy efficient multipath routing in space division multiplexed elastic optical networks. *Computer Networks*, 244:110349.

Ju, M., Liu, Y., Zhou, F., and Xiao, S. (2022). Disaster-resilient and distance-adaptive services provisioning in elastic optical inter-data center networks. *Journal of Lightwave Technology*, 40(13):4064–4077.

Khorasani, Y., Ghaffarpour Rahbar, A., and Jafari-Beyrami, M. (2023). Fragmentation management to reduce bandwidth wastage in sdm-eon networks. *Photonic Network Communications*, 46(2):51–67.

Liu, H., Ren, J., Chen, Y., Hu, J., Tang, C., and Tang, M. (2022). Spectrum slicing-based fragmentation aware routing and spectrum allocation in elastic optical networks. *Optical Switching and Networking*, 45:100673.

Liu, L., Chen, B., Ma, W., Chen, H., Gao, M., Shao, W., Wu, J., Peng, L., and Ho, P.-H. (2023). Selective resource offloading in cloud-edge elastic optical networks. *Journal of Lightwave Technology*, 41(20):6431–6445.

Moura, P. M. and Drummond, A. C. (2025). FlexGridSim: Flexible Grid Optical Network Simulator. Available at: `http://www.lrc.ic.unicamp.br/FlexGridSim/`.

Panayiotou, T., Michalopoulou, M., and Ellinas, G. (2023). Survey on machine learning for traffic-driven service provisioning in optical networks. *IEEE Communications Surveys Tutorials*, 25(2):1412–1443.

Rezaee, A., McCann, R., and Vokkarane, V. M. (2024). Dynamic crosstalk-aware routing, modulation, core, and spectrum allocation for sliceable demands in sdm-eons. In *2024 IEEE 30th International Symposium on Local and Metropolitan Area Networks (LANMAN)*, pages 76–81.

Sudhakar, Khan, A. M., and Batham, D. (2024). Future generation elastic optical networks: A state-of-art review. In Nanda, S. J., Yadav, R. P., Gandomi, A. H., and Saraswat, M., editors, *Data Science and Applications*, pages 397–410, Singapore. Springer Nature Singapore.

Villamayor-Paredes, M. M. R., Maidana-Benítez, L. V., Colbes, J., and Pinto-Roa, D. P. (2023). Routing, modulation level, and spectrum assignment in elastic optical networks. a route-permutation based genetic algorithms. *Optical Switching and Networking*, 47:100710.

Zou, R., Lin, S.-C., Matsuura, M., Hasegawa, H., and Subramaniam, S. (2024). Drama-dc: Disaster recovery algorithm with mitigation awareness in data center eons. In *2024 International Conference on Optical Network Design and Modeling (ONDM)*, pages 1–6.