Analysis of Communication in Elastic Optical Networks between Data Centers

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Abstract. *The rapid growth of internet traffic, driven by video streaming, cloud computing, and IoT, is straining traditional optical backbones nearing their capacity limits. Elastic Optical Networks (EONs) address these challenges by enabling dynamic bandwidth allocation with flexible grid technology, improving spectral efficiency. Space-Division Multiplexing (SDM) further enhances capacity through multi-core and multi-mode fibers, offering scalable solutions for future traffic demands. Within Data Center Networks, Elastic Optical Data Center Networks (EODCNs) combine EON and SDM principles to deliver efficient infrastructures capable of supporting the increasing demands of modern digital ecosystems. Our work proposes a routing algorithm for this network model that is capable of enhancing data delivery with an emphasis on satisfying more connections between DCs when compared to other works in the literature.*

1. Introduction

The amount of data transferred on the internet around the world has reached unparalleled levels, which were hardly foreseeable at the origin of communication. The proliferation of video streaming, cloud computing, social networks and the Internet of Things (IoT) characterize the bulk of the data transmitted [Panayiotou et al. 2023]. Globalization and ease of access allow the number of users to grow, entrusting the network with data on a global scale. Innovations such as 5G/6G networks, edge computing and real-time applications amplify this growth, with new requirements and traffic profiles, exposing the need for a robust and scalable infrastructure to meet demand [Hosseini et al. 2024]. These are the challenges that existing communication networks must meet, developing to deal with the need for bandwidth, low latency and reliability.

Despite many advances in network technologies, the world's communication network is reaching its limits when it comes to transmitting the exponentially growing traffic of recent years. The traditional Wavelength Division Multiplexing (WDM) architecture operates close to its maximum transmission capacity defined by the Shannon Limit [Ahmed et al. 2024], which details the maximum information capacity carried by a single fiber. The fixed-grid characteristic of this model is a major challenge in the bandwidth allocation process, as modern traffic is characterized by being very dynamic in terms of requirements, e.g. it is rigidly distributed in slices with greater capacity, which overlaps with demand [Radovic et al. 2024]. As a result, allocation is not efficient, highlighting the need for new solutions to ensure sustainable network scalability.

Elastic Optical Networks (EONs) have emerged as a promising solution to address these challenges [Sudhakar et al. 2024]. This architectural model proposes a paradigm shift in the frequency grid, where WDM has a wider fixed-grid, while EONs use a finer-grid technology. This feature allows bandwidth allocation to be better adjusted to demand, which is very dynamic. In this way, spectrum allocation can achieve higher utilization efficiency. This flexibility makes EONs particularly well-suited to handle diverse traffic demands, from high-throughput applications to latency-sensitive services. To manage resources in this network model, the algorithms proposed are known as Routing and Spectrum Allocation (RSA) algorithms [Pinto-Rios et al. 2024].

The Space Division Multiplexing (SDM) technique applied to EONs represents a significant step forward in overcoming the limitations of the current optical backbone. The insertion of the spatial dimension, either through the use of multicore fibers or multimode fibers, increases the number of transmission channels in a communication link. When they are combined into a single model called Space Division Multiplexing Elastic Optical Networks (SDM-EONs) [Hafezi and Ghaffarpour Rahbar 2024], these networks can guarantee substantial gains in capacity and a scalable network. These networks are ideal for handling future traffic demands with the growth in new applications, as well as maintaining energy efficiency and operating costs. To solve the problems that arise in this type of network, Routing, Spectrum, and Core Allocation (RSCA) algorithms have emerged, capable of managing resources [Rizk-Allah and Elsodany 2024].

Two problems accompany routing and allocation in this network model: inter-core crosstalk and spectrum fragmentation. Inter-core crosstalk occurs when requests are served on neighboring cores and use the same frequency band on their respective cores [Hamad et al. 2024]. There is a limit to how much interference the transmission can accept without compromising the signal, so there is some complexity in selecting the modulation. Fragmentation are constant allocation and removal, which generate small gaps in the spectrum that are not sufficient for subsequent transmissions [Lacerda Jr et al. 2024]. In order to maximize the spectrum usage, adaptive modulations are applied, thus packing a greater number of bits per transmitted symbol. Decoding is an essential stage in the transmission process, so it is important to observe the limitations imposed by the modulation, such as the maximum transmission distance without data compromised. To deal with this problem, an algorithm called Routing, Modulation Level, Spectrum, and Core Allocation (RMLSCA) emerged [Rodrigues et al. 2022].

Data center communication traffic plays a key role in processing, storing and distributing information globally. This traffic between data centers is characterized by high bandwidth demands, low latency and dynamic workload shifts [Gupta et al. 2024]. Numerous applications such as distributed machine learning, real-time communication, and cloud services require efficiency and reliability. The explosive growth in traffic has intensified the need to develop traditional networks to deal efficiently with the allocation of data center resources. Data Center Networks (DCNs) make up the core of modern communication infrastructure [Pathan et al. 2024], enabling worldwide connection and data sharing. DCNs must meet throughput, latency, and scalability requirements to support applications that traditional architecture often falls short of.

By integrating the three principles discussed above, Space Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs) emerge [Ahmadi et al. 2024], offering flexibility and efficiency when allocating resources for network calls, as well as supporting intra- and inter-datacenter communication and its specifications. Spectrum elasticity is able to allocate the heterogeneous and dynamic demands of the network, optimizing the use of optical resources while guaranteeing high performance, high data throughput and energy efficiency. In this way, SDM-DC-EONs represent the foundation of the infrastructure capable of supporting digital communication.

In this paper, we propose a Routing, Modulation Level, Spectrum, and Core Allocation Algorithm (RMLSCA) for Space Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs), which aims to reduce the number of blocked transmissions in the network, maximize the spectrum usage and reduce fragmentation, and jointly support the data center communication present in the network. The results show that the algorithm outperforms other proposals in the literature by up to three orders of magnitude by performing a broader search in network cores.

This paper is organized as follows. Section 2 outlines the state-of-the-art of Space Division Multiplexing architectures and Data Center Elastic Optical Networks. Section 3 describes the Centerclare Algorithm. Section 4 discusses the simulation metrics and the results obtained. Finally, Section 5 presents the conclusion.

2. Related Works

In recent years, advances in the technologies applied to networks and cloud computing have required the development of new mechanisms that are sufficiently capable of handling the high volume of data at a very high rate of speed. Studies have investigated numerous approaches to improving network performance, such as adding the spatial dimension to the Elastic Optical Network model, combining this technology with the Data Center Network. The result of this combination is the Space-Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs).

To facilitate data exchange in SDM-EONs, [Hosseini et al. 2024] introduced an innovative dynamic multipath routing algorithm aimed at minimizing blocking probability, bandwidth usage, and energy consumption by Bandwidth Variable Transponders (BVTs). Their approach utilizes multiple lightpaths while maintaining the same set of fibers, ensuring that differential delay remains manageable. The study evaluates the efficiency of the modulation format and takes inter-core crosstalk constraints into account. However, despite focusing on data flow within the SDM-EONs architecture, the research does not incorporate data center elements in the network.

Machine learning techniques also are applied to resource management. In [Asiri and Wang 2024], Deep Reinforcement Learning was utilized for Quality of Transmission-aware (QoT-Aware) flow routing in Elastic Optical Networks. The agent learns from Routing, Modulation, and Spectrum Assignment (RMSA) policies, improving its decision-making to optimize network spectrum utilization. To assess QoT, the study considers additional factors such as physical impairments, spectrum fragmentation, and traffic dynamics. The reward helps the agent identify a lightpath that satisfies QoT requirements while reducing blocking ratio and supporting higher bit rate. However, the study does not incorporate SDM as part of network allocation. The core and spectrum allocation sub-problem addressed in our work has a comparable counterpart in this study, but it only accounts for the spectrum of a single core when handling requests.

[Agarwal and Bhatia 2024] introduced a meta-heuristic approach based on a Genetic Algorithm (GA) for Routing, Modulation, and Spectrum Allocation. Their study evaluates the performance of single-path and multi-path routing by analyzing the blocking probability in simulated networks. The proposed algorithm identifies the most optimal solution. However, the authors do not take data center elements into account and do not consider spatial flexibility in the network. As a result, intrinsic challenges like inter-core crosstalk are not addressed, simplifying the complexity of resource allocation within a network link.

[Villamayor-Paredes et al. 2023] tackled a subset of the problem, specifically RMLSA. They proposed two Genetic Algorithm (GA)-based approaches that enable route permutation. The algorithm determines the path, selects the appropriate modulation format, and assigns resources to the lightpath, aiming to minimize both the maximum frequency slot rate used and the blocking ratio for dynamic traffic. While GA is utilized for resource allocation, the spatial dimension is not considered, simplifying the problem by assigning requests to a single core. Additionally, the proposed scenario does not incorporate nodes as data centers, treating all nodes as homogeneous.

[Chen et al. 2023] explore the resource allocation problem in SDM-EONs, introducing a parameterization strategy that represents spectrum sensitivity (SS) in a matrix concerning core crosstalk. They propose an Integer Linear Programming (ILP) model that incorporates a crosstalk-sensitive constraint to enhance spectrum efficiency. The study presents three heuristics focused on core allocation with SS, demonstrating the best balance between average crosstalk and spectrum efficiency in both static and dynamic network scenarios. While the research considers the SDM and tackles network allocation challenges, it does not differentiate data center flows in the allocation.

To take advantage of the network's high flexibility and mitigate one of its major challenges, bandwidth fragmentation, [Khorasani et al. 2023] propose a novel spectrum allocation policy for EONs called Smart-Fit. This approach identifies and stores spectrum gaps that precisely match the request size, enabling an optimized best-fit allocation. Additionally, they introduce a multipath routing algorithm per core, demonstrating significant scalability, reduced fragmentation, and lower transponder usage. The combination of these two strategies proves effective in minimizing both spectrum waste and fragmentation. However, while the multipath/multicore allocation policy addresses fragmentation, it does not consider the data center scenario.

Addressing the critical issue of fragmentation in EONs, [Hafezi and Ghaffarpour Rahbar 2024] introduce two novel algorithms designed to reduce fragmentation and lower network blocking. One algorithm prioritizes frequency range selection, while the other focuses on core allocation. The proposed scenario considers demands with three priority levels, ensuring resource allocation accordingly. However, the study solely tackles the RMSA problem, without accounting for the spatial dimension or data center networks.

[Rezaee et al. 2024] introduced a crosstalk-aware routing algorithm to address a key challenge in Multicore Fibers (MCF), defining two policies based on calculated crosstalk levels. Additionally, they propose a novel resource allocation approach incorporating crosstalk-aware bandwidth slicing. This method not only mitigates crosstalk but also improves bandwidth allocation by allowing high-demand requests to be slotted into newly available regions, effectively reducing fragmentation. However, the study does not take Data Center Networks into account for routing and flow management.

The growing demand for task offloading driven by emerging applications is addressed by [Chen et al. 2024]. Their goal is to optimize network resource allocation and minimize end-to-end latency by determining whether and where to offload users in Cloud-Edge Elastic Optical Networks (CE-EONs). They propose an Integer Linear Programming (ILP) model as an initial solution, along with several heuristics to manage partial resource offloading. The study emphasizes the effectiveness of the Proportional Segment Approach in achieving the lowest end-to-end latency, reducing blocking probability, and optimizing network resource allocation in dynamic scenarios.

The authors [Ju et al. 2022] consider critical network situations, where the survival of communication is necessary. For this reason, it adopts a disaster prevention policy through the use of multipaths for DC communication. An ILP is developed and adaptive modulations are applied to the routing process, as well as backup routes. The authors [Liu et al. 2022] propose a solution for spectrum allocation, based on a spectrum slicing strategy that seeks to reduce fragmentation in elastic optical networks. This model does not exploit the multicore dimension or DC communication elements.

While the studies mentioned above and found in the literature address various challenges in elastic optical networks, they often break these issues down into smaller, isolated components. Notably, the core allocation problem is frequently neglected in research that assumes optical fibers contain only a single core. In contrast, our approach provides a holistic solution by integrating routing, allocation, and request management in Data Center Networks alongside Space Division Multiplexing Elastic Optical Networks. This results in a more comprehensive strategy for tackling the complexities of these systems.

Table 1. State-of-the-art literature characteristics.

Paper	SDM	Crosstalk	Spectrum Efficiency	Data Center
[Hosseini et al. 2024]	✓	✓	✓	
[Asiri and Wang 2024]			✓	
[Agarwal and Bhatia 2024]			✓	
[Villamayor-Paredes et al. 2023]			✓	
[Chen et al. 2023]	✓	✓	✓	
[Khorasani et al. 2023]	✓	✓	✓	
[Hafezi and Ghaffarpour Rahbar 2024]			✓	
[Rezaee et al. 2024]	✓	✓	✓	
[Chen et al. 2024]			✓	✓
[Ju et al. 2022]			✓	✓
[Liu et al. 2022]			✓	
Centerclare	✓	✓	✓	✓

3. Centerclare Algorithm

This section introduces the Routing, Modulation Level, Spectrum, and Core Allocation for SDM-DC-EONs (Centerclare) Algorithm. The algorithm seeks to establish communication when point-to-point resources are available. To do this, data center nodes are chosen and network traffic is generated. The specific communication between Data Center nodes is characterized by the massive amount of data transferred, so the strategy adopted is to allocate less congested routes, since this type of request is not sensitive to response time. For the other network connections, the shortest routes are allocated to meet the needs of the transmission. Six different modulations are available for application, based on the transmission range that each one allows (Table 2). The core and spectrum restrictions (continuity and contiguity) are respected in order to keep the transmission transparent, i.e. only in the optical medium and without the need for electrical conversion.

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. 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.

Table 2. Modulation Characteristics.

Modulation Level	# Bits Per Symbol	Slot Capacity (Gbps)	Transmission Reach (Km)
64QAM	6	75	125
32QAM	5	62.5	250
16QAM	4	50	500
8QAM	3	37.5	1000
QPSK	2	25	2000
BPSK	1	12.5	4000

3.2. Algorithm Operations

The Centerclare is an RLMSCA algorithm for SDM-DC-EONs that can be employed for different loads, scenarios, and topologies. The algorithm's main objective is to reduce the number of blocked connections, as well as guaranteeing reliability of use and providing communication connections that are not negatively impacted by transmission between data centers.

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 1, the algorithm starts by mapping the network resources that are available for allocation. Then, when topology recognized, $k = 2$ data centers are dynamically positioned in nodes that will receive both data center flows and regular network communication. The nodes are selected by the traffic characteristics, considering the two nodes with more flow. The reference algorithm considers backup paths for disaster scenario, which we do not use in this case. This way there is a relaxation of the original proposal, considering only elements present in our approach when generating the data flow. There is a greater flow in specific network nodes, directed where the data centers are.

In Line 3, it runs the algorithm for each of the network requests. In Line 4, it finds a set of five shortest paths between the source and destination nodes. In Line 5 the set of paths are inverted if the transmission is DC to DC, sorting by the longest to the shortest. In Line 8, each path is measured with its set of edges, cores, and slots. For each of the routes found, the fragmentation and crosstalk levels are calculated. If the the levels are acceptable, the resource is allocated.

When communication enters a route, the core and slot pair is searched for. The set of slots required is compatible with the bandwidth requested, so there must be a sequence of slots available to allocate. If the path is found, the lightpath is immediately returned, otherwise another path is tested. The algorithm then runs until the set of paths is exhausted or the lightpath is found.

The complexity of the Centerclare 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 Centerclare is $O(KV(V + E)logV)$.

4. Evaluation

This section provides a detailed explanation of how the proposed work was evaluated. It describes the metrics used to measure performance. Additionally, it presents a discussion of the results, implications and impact on the context of the study.

4.1. Simulation

The simulations were conducted using the Flexgridsim simulator, which is specifically designed for Elastic Optical Networks and also supports Space Division Multiplexing, with customizations for Data Center Networks [Moura and Drummond]. Network requests were previous generated following a Poisson distribution with 100,000 network calls, 30% of which involved data center nodes. A 95% confidence interval was used to analyze the results obtained. Two topologies were considered for this study: the NSF topology (Figure 1(a)), with links more distant and few connections, and the PAN topology (Figure 1(b)), with shorter links and much more options from node to node, i.e. more connections. The first algorithm [Ju et al. 2022], referenced as "Fragmentation", aims to reduce blocking and fragmentation, though it does not account for networks utilizing Spatial Division Multiplexing. The second algorithm [Liu et al. 2022], referenced as "Datacenter", focuses on handling requests that arrive within the network and are directly associated with the network's data centers.

4.2. Results

This section shows the results obtained in simulation, with evaluation discussed below. The metrics evaluated were: Bandwidth Blocking Ratio (BBR), which is the ratio between

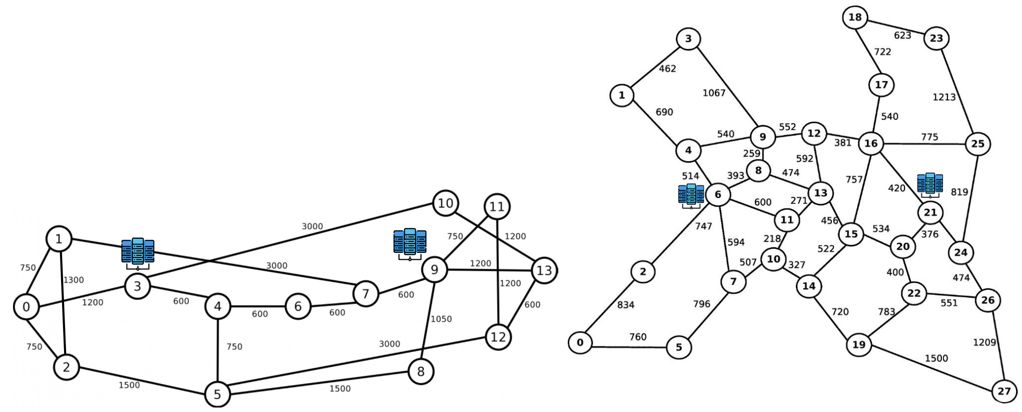
Algorithm 1: Centerclare

```
Input  : Network Traffic, Vertices, Edges, Cores, Slots
Output: Lightpath Connection

Mapping network resources for allocation
Positioning() function for data center nodes
for request in Network Traffic do
    Find set of shortest path for transmission
    if request is DC-to-DC then
        Invert the sequence in set of paths
    end
    for path in set of paths do
        Apply modulation according to distance
        for edge in Edges do
            for core in Cores do
                for slot in Slots do
                    Compute Fragmentation Level
                    Compute Intercore Crosstalk level
                    Calculate if the (core, slot) + bandwidth next slots are
                      available
                    return: lightpath resources
                end
            end
        end
        if Fragmentation or Crosstalk higher than acceptable for all
          combination then
            Remove from set of paths
        end
    end
    return
end
```

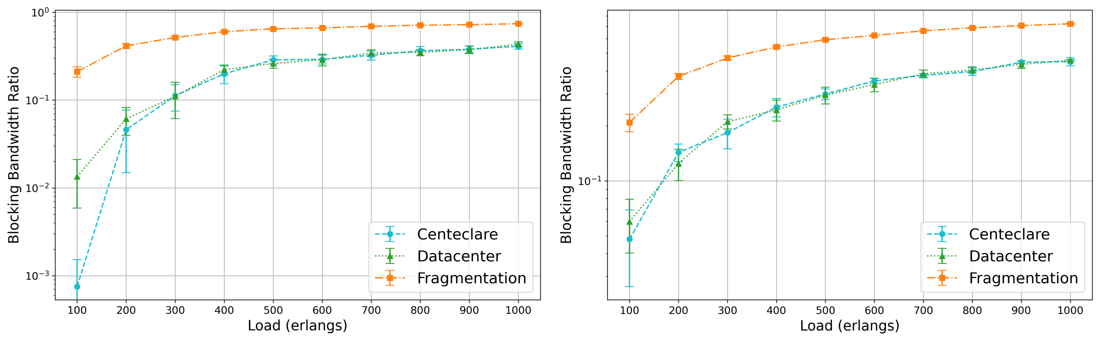
the total number of calls arriving on the network and the number of calls that were rejected due to there being no resources available for allocation; Data Transmitted (DT), which is the sum of the bandwidth transmitted on the network by all accepted calls; Data Center Traffic Blocked (DCB), which analyzes only the portion of traffic that communicates between two data center points; Energy Efficiency (EE), which is the total energy consumption of the network over the total amount of data transmitted; Fragmentation (FR), which evaluates the sequence of available and used slots within a fiber. Average Hops per Lightpath (AHL), which is the average number of hops for accepted transmissions; Crosstalk per Slot Ratio (XT), which is the metric that checks the level of interference between cores for neighboring transmissions.

Figure 2 shows the Bandwidth Blocking Ratio for the NSF (Figure 2(a)) and PAN (Figure 2(b)) topologies. For the NSF topology, the blocking of the Centerclare algorithm is lower at lower loads by up to two orders of magnitude, remaining below the Fragmen-



(a) NSF (b) PAN

Figure 1. Topologies with two positioned data centers.



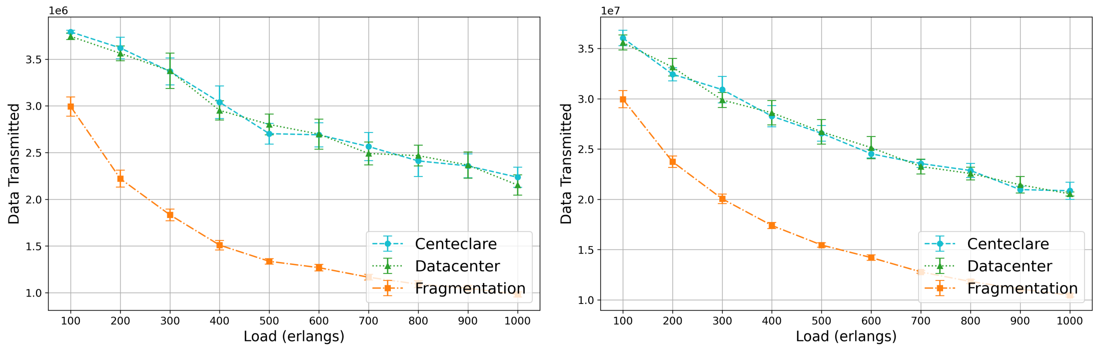
(a) NSF (b) PAN

Figure 2. Blocking Bandwidth Ratio

tation algorithm, and below the Datacenter algorithm for initial loads and getting closer at higher loads. For the PAN topology, the Centerclare algorithm has lower results than Fragmentation algorithm for all simulated loads, while it has results close to Datacenter algorithm. The result presented is positive because it combines the two request situations, both for regular flow and for data center communication, while the other algorithms perform best when allocating regular communication (Fragmentation algorithm) and allocating data center communication (Datacenter algorithm). The Centerclare algorithm's proposal is to handle the flow of transmissions in the network while also actively allocating resources to the data center network, so it's a strong point to guarantee resources for both while outperforming other algorithms.

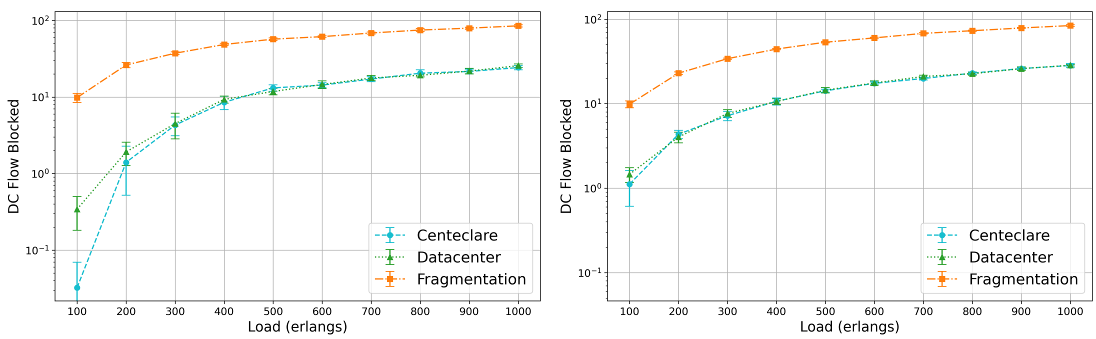
Figure 3 shows the result of Data Transmitted for the simulated algorithms. For the NSF topology (Figure 3(a)), the Fragmentation algorithm shows the lowest amount of data transmitted, which can be related to the previous result of bandwidth blocking, while the Centerclare and Datacenter algorithms show close results, reinforcing the correlation with the bandwidth blocking result. The same is true of the PAN topology (Figure 3(b)), where the trend continues and the Frag algorithm shows the lowest result in terms of data transmitted, followed by the Datacenter and Centerclare algorithms.

Figure 4 shows the amount of traffic blocked specifically when communicating



(a) NSF (b) PAN

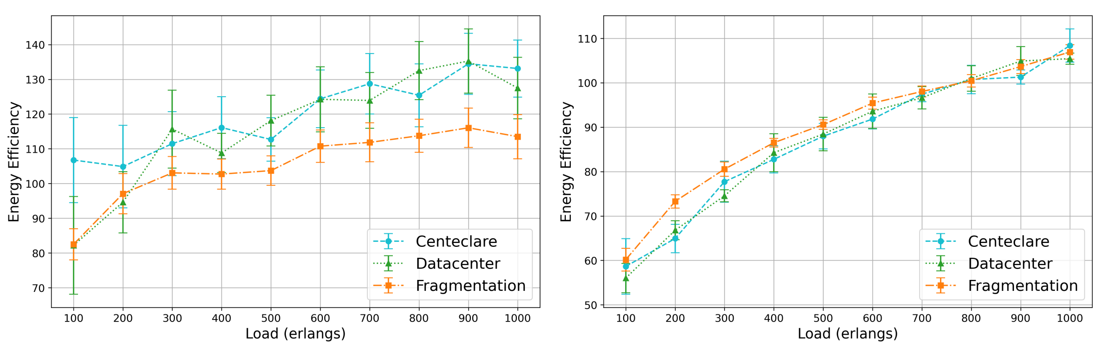
Figure 3. Data Transmitted



(a) NSF (b) PAN

Figure 4. Data Center Traffic Blocked

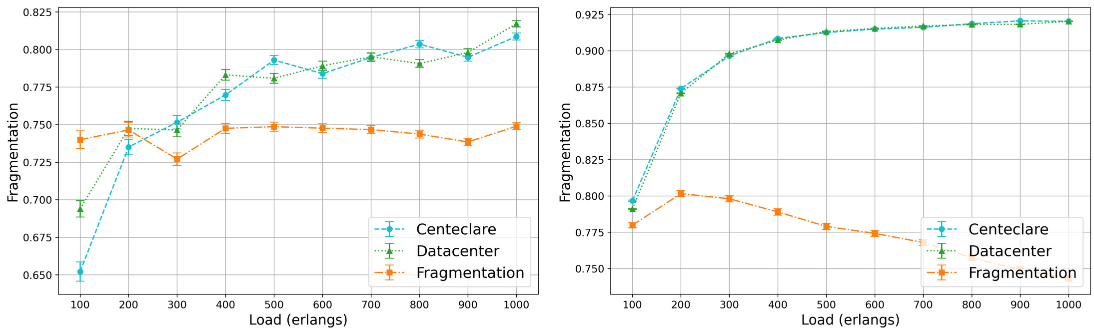
between data centers. For both results (Figures 4(a) and 4(b)), the Centerclare algorithm outperformed the Fragmentation algorithm for all simulated loads. It also performed better than the Datacenter algorithm at lower loads and matched its performance at higher volumes. The goal of Centerclare is to efficiently support both communication scenarios: regular flows between network nodes and transmissions between data centers. The results show that it achieves this objective while maintaining a low blocking rate compared to the reference algorithms.



(a) NSF (b) PAN

Figure 5. Energy Efficiency

Figure 5 shows the Energy Efficiency of the simulated algorithms for the two topologies. For NSF topology (Figure 5(a)), the Fragmentation algorithm shows the worst efficiency, while the Datacenter and Centerclare algorithms alternate over the simulated loads, with Centerclare algorithm showing slightly better results. This is due to the fact that the algorithm is not able to transmit as much data as those compared, but uses a large part of the links, considering that the topology has fewer connections. For the PAN topology (Figure 5(b)), the Fragmentation algorithm is more efficient due to the number of links, as it is a more connected topology. This way, the links are better utilized despite the large amount of blocking. However, the Centerclare algorithm closely follows efficiency, with much more data transmitted and less blocking, using more resources and transmitting efficiently.



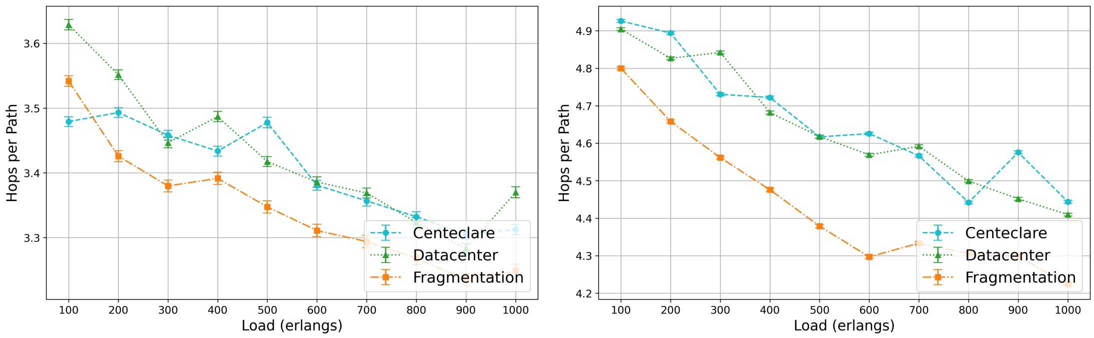
(a) NSF (b) PAN

Figure 6. Fragmentation

Figure 6 shows the results of network spectrum Fragmentation throughout the simulations of the two topologies. For PAN topology (Figure 6(b)), the Fragmentation algorithm shows less fragmentation throughout the simulations because it is the main objective of the proposal, but with fewer calls accepted in the topology than the other algorithms compared. In this way, the dynamic allocation of resources favors the fragmentation of algorithms that reject more requests. Meanwhile, in the NSF topology (Figure 6(a)), there is a variation in the level of fragmentation between the and Datacenter algorithms, with Centerclare showing a lower level of fragmentation for lower loads and remaining reasonable at high loads.

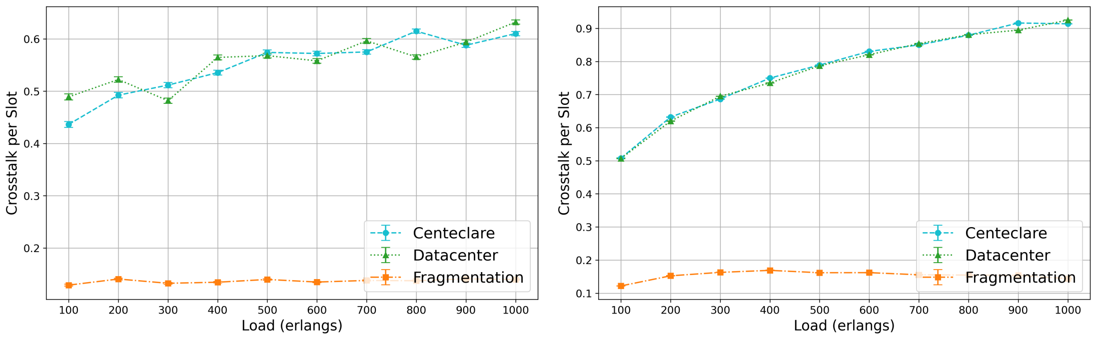
Figure 7 shows the Average number of Hops per Lightpath allocated in the simulation of the algorithms for the NSF and PAN topologies. Both Figures (Figure 7(a) and 7(b)) show that the average of the Fragmentation algorithm is lower because it allocates fewer transmissions, while the Datacenter algorithm has a higher average than the other algorithms. The Centerclare algorithm has a higher average than the Fragmentation algorithm because it allocates more requests, and an average close to the Datacenter algorithm, ensuring that a large amount of network resources are used. It should be noted that the NSF topology has a lower average number of hops because it is a network with fewer nodes and links than the PAN.

Figure 8 shows the level of crosstalk per slot for the two topologies for all the simulated algorithms. With low call acceptance, the Fragmentation algorithm is expected to have lower crosstalk values for both situations. Meanwhile, the algorithms with less



(a) NSF (b) PAN

Figure 7. Average Hops per Lightpath



(a) NSF (b) PAN

Figure 8. Crosstalk per Slot Ratio

blocking have a higher level of crosstalk interference between cores. Thus, the Datacenter algorithm has values just above the Centerclare algorithm for the NSF topology (Figure 8(a)), while the two remain fairly close in the PAN topology (Figure 8(b)).

5. Conclusion

In conclusion, the exponential growth of internet traffic and the rising demands of data center applications highlight the urgent need for scalable, efficient, and adaptable network solutions. Elastic Optical Networks (EONs) and Space-Division Multiplexing (SDM) technologies address the limitations of traditional optical backbones, providing the flexibility and capacity required to meet diverse and dynamic traffic patterns. When integrated into data center networks, Space Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EONs) offer a powerful framework to support modern applications, ensuring high performance, resource efficiency, and future scalability. These advancements are critical for building resilient and sustainable network infrastructures in the face of ever-growing digital demands.

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References

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

[Ahmadi et al. 2024] 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.

[Ahmed et al. 2024] Ahmed, I., Oki, E., and Chatterjee, B. C. (2024). Blocking probability analysis modeling in spectrally-spatially elastic optical networks: A crosstalk-avoided perspective. In *2024 24th International Conference on Transparent Optical Networks (ICTON)*, pages 1–4.

[Asiri and Wang 2024] 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.

[Chen et al. 2023] 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 et al. 2024] 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.

[Gupta et al. 2024] Gupta, R., Aggarwal, M., and Ahuja, S. (2024). A novel framework for content connectivity through optical data centers. *Journal of Optical Communications*, 44(s1):s971–s977.

[Hafezi and Ghaffarpour Rahbar 2024] 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.

[Hamad et al. 2024] Hamad, Q. S., Saleh, S. A. M., Suandi, S. A., Samma, H., Hamad, Y. S., and Hussien, A. G. (2024). A review of enhancing sine cosine algorithm: Common approaches for improved metaheuristic algorithms. *Archives of Computational Methods in Engineering*, pages 1–58.

[Hosseini et al. 2024] 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 et al. 2022] 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 et al. 2023] 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.

[Lacerda Jr et al. 2024] Lacerda Jr, J. C., Morais, A. G., Cartaxo, A. V., and Soares, A. C. (2024). A new algorithm to mitigate fragmentation and crosstalk in multi-core elastic optical networks. In *Photonics*, volume 11, page 504. MDPI.

[Liu et al. 2022] 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.

[Moura and Drummond] Moura, P. M. and Drummond, A. C. FlexGridSim: Flexible Grid Optical Network Simulator. http://www.lrc.ic.unicamp.br/FlexGridSim/.

[Panayiotou et al. 2023] 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.

[Pathan et al. 2024] Pathan, M. N., Muntaha, M., Sharmin, S., Saha, S., Uddin, M. A., Nur, F. N., and Aryal, S. (2024). Priority based energy and load aware routing algorithms for sdn enabled data center network. *Computer Networks*, 240:110166.

[Pinto-Rios et al. 2024] Pinto-Rios, J., Dumas Feris, B., Vasquez, C., Saavedra, G., Borquez-Paredes, D., Jara, N., Olivares, R., Amjad, S., Leiva, A., and Mas-Machuca, C. (2024). Benchmarking framework for resource allocation algorithms in multicore fiber elastic optical networks. *Journal of Optical Communications and Networking*, 16(11):G11–G27.

[Radovic et al. 2024] Radovic, M., Sgambelluri, A., Cugini, F., and Sambo, N. (2024). Power-aware high-capacity elastic optical networks. *Journal of Optical Communications and Networking*, 16(5):B16–B25.

[Rezaee et al. 2024] 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.

[Rizk-Allah and Elsodany 2024] Rizk-Allah, R. M. and Elsodany, E. (2024). An improved rough set strategy-based sine cosine algorithm for engineering optimization problems. *Soft Computing*, 28(2):1157–1178.

[Rodrigues et al. 2022] Rodrigues, E., Rosário, D., Cerqueira, E., and Oliveira, H. (2022). Analysis of routing and resource allocation mechanism for space-division multiplexing elastic optical networks. *IEEE Transactions on Network and Service Management*, 20(1):762–773.

[Sudhakar et al. 2024] 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 et al. 2023] 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.