Efficient Request Management in Data Center Elastic Optical Networks

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Abstract—The service model is constantly changing on the Internet, and the most prominent model in recent years is the use of cloud computing. The more connected world has generated new needs that must be met by the core of the network in order for the Internet to function. Communication at high speeds, always available and efficient is vital if demand is to be met. The characteristics of this traffic have prompted the development of new mechanisms to deal with the increasing rate of data transmitted over the network. Innovations at earlier layers of the network are emerging, and the proposal for flexible spectrum links is proving to be very promising for meeting the heterogeneous requests coming in. In this context, this paper proposes a routing algorithm for the SDM-DC-EONs network model. The proposed solution presents results that surpass models in the literature by up to two orders of magnitude when it comes to establishing transmissions in the network, represented by the Bandwidth Blocking Ratio.

Index Terms—Data Center, Elastic Optical Networks, Routing, Space Division Multiplexing

I. Introduction

The data flow in the network has increased intensively in recent years, largely due to the widespread adoption of devices connected. Smartphones and smart devices, combined with Internet of Things (IoT), 5G networks, and cloud computing have created new demands on communication. However, the current network's infrastructure core is not prepared to deal with the modern demands [1], struggling with transmissions that require ultra-low latency and massive data transfers. New solutions need to be proposed [2] to ensure the future of communication. These solutions must not only address the current limitation but also anticipate the future needs.

Cloud services have become responsible for a large share of modern traffic. And that is due to its versatility in storing, processing and transmitting massive data. Cloud computing supports a variety of applications, from cloud storage to real-time communication [3]. However, these applications also introduce new challenges for network infrastructure. Applications that require low latency and high availability to ensure user experience high level. Consequently, there is an urgent need for more robust mechanisms so the infrastructure is sufficient for communication around the world [4].

The traditional network infrastructure, with fixed spectrum frequency is not very dynamic, lacking the flexibility to handle the increasing volume traffic. The growth in the amount of data transmitted exposes these network's limitations. Elasticity is a feature of the network architecture proposed in Elastic Optical Networks [5], which makes better use of the spectrum by dividing the frequency into smaller slices. This allows the allocated bandwidth to be very close to that required by the transmission, reducing spectrum waste and data losses. The potential of this model is efficient spectrum allocation, improving network conditions.

The flexibility of the links improves allocation, avoiding underutilization of resources, but does not increase the total network's transmission capacity. With the aim of enhancing the network, there is a proposal to add spatial dimension to the physical layer, showing significant gains in the transmission rate. The combination of spectrally and spatially flexible links presents a significant gain, meeting the need for the network's new point-to-point demands. The result is the Spatial Division Multiplexing Elastic Optical Networks [6]. In this model, network resources are allocated more efficiently, optimizing data transmission and reducing network bottlenecks.

The allocation of resources in this network gives rise to the problem of Routing and Allocation of Modulation, Spectrum and Core. In addition, two problems arise from this model: the inter-core crosstalk (XT) problem and fragmentation [7]. XT occurs when using multiple cores on the same frequency band at the same time [8]. Physical interference between transmissions attenuates the signal, making it hard when decoding. So it is important to check the interference level and ensure the integrity of the signal. Fragmentation is caused by the frequent allocation and removal, resulting in small gaps that are not enough for new demands [9]. Both problems increase the complexity of the overall resource allocation problem.

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, maximize the spectrum usage and reduce fragmentation, while supporting the Data Center communication in the network. The results show that the algorithm outperforms the compared algorithms by up to two orders of magnitude by performing a broader search in network cores.

This paper is organized as follows. Section II outlines the state-of-the-art spectrally and spatially flexible grid architectures and Data Center Elastic Optical Networks. Section III describes the Entrainer Algorithm. Section IV discusses the simulation and the results obtained. Finally, Section V presents the conclusion.

II. 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 deal with huge data transmitted, Hosseini et. al. [2] proposed a dynamic multipath routing algorithm. The proposal reduces bandwidth blocking probability and energy consumed by the Bandwidth Variable Transponders (BVTs). They use multiple light paths, but the same set of fibers, i.e. the same route. In this way, they can ensure that differential delay is not a problem. Various modulation levels are considered, and core restrictions are applied with regard to crosstalk. Despite dealing with data flow in the SDM-EONs architecture, the work does not consider data center elements. Hafezi and Rahbar [7] 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, that can allocate demands in new regions, reducing fragmentation. The work does not consider Data Center Networks for routing and handling flows.

Asiri and Wang use Machine Learning for resource management [10], applying Deep Reinforcement Learning to a Quality of Transmission-aware (QoT-aware) routing solution in Elastic Optical Networks. The agent learns about Routing, Modulation, and Spectrum Assignment (RMSA) policies maximize spectrum usage, considering factors of physical interference, spectrum fragmentation and traffic dynamics. The reward makes the agent find the best available compatible lightpath with QoT requirements, so that the result is less blockage in the network with high throughput. The work does not include space division multiplexing in resource allocation. The core and spectrum allocation sub-problem present in our work has its parallel in a simplified form in this work, considering the spectrum of only one core for adjusting requests.

Following the critical problem of fragmentation in EONs, [9] 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.

Zou et. al. [11] take care of disasters in the network by 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 is not multi-mode/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. [12]. 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.

Although the works mentioned before solve problems arising from elastic optical networks, they usually break down the problems into smaller ones. The core allocation problem is disregarded in works where the fiber has only one core. Our proposal presents a complete solution regarding routing, allocation, and request handling in Data Center Networks combined with Space Division Multiplexing Elastic Optical Networks.

III. Entrainer Algorithm

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

A. Network Overview

The Space-Division Multiplexing Elastic Optical Networks use the Spatially Flexible Reconfigurable Optical Add/Drop Multiplexers (ROADM) equipment, which enables wavelength-selective switch and space-wavelength granularity, as well as using Multiple-Input Multiple-Output (MIMO) transceivers at its core.

In order to achieve core multiplexing, each link in the network uses Multicore Fibers (MCF). There are seven different cores arranged in a hexagonal shape, with 320 frequency slots available, each sliced into 12.5 GHz. The links between a pair of nodes are bidirectional, and the distance is measured in kilometers between them. Figure 1 illustrates the nodes in a round shape, connected to each other by a line indicating the distance in kilometers, and represents two datacenter nodes by the blue drawing. The network devices do not allow cores to be exchanged during a transmission, i.e. the same core is maintained for all the links in the path.

In this paper, we employ 64QAM, 32QAM, 16QAM, 8QAM, QPSK, and BPSK modulation formats for extensions

of 125, 250, 500, 1000, 2000, and 4000 km respectively with slot capacities of 75, 62.5, 50, 37.5, 25, and 12.5 gigabits per second (Gbps). The connection's Quality of Transmission (QoT) is directly related to the transmission distance and, consequently, the level of modulation that will be selected. The number of slots needed to satisfy demand is calculated from the modulation applied, varying the bit rate that can be transmitted in a single slot. Different transmissions are separated by a Filter Guard Band (FGB) which occupies a single slot regardless of the modulation.

B. Entrainer Operations

The Entrainer is an RLMSCA algorithm for SDM-DC-EONs that has been simulated for different loads, scenarios and topologies. The proposed algorithm reduces the number of blocked requests and increases the total network throughput.

The Algorithm 1 describes how are the operations. The input is the set of network's information composed of Vertices, Edges, Cores, Slots and Requests. The expected output is the connection with lightpath and enough resources allocated to the request. In Line 1, the topology is mapped into nodes and links, then in Line 2, $dc = 2$ nodes are selected for positioning data centers, as presents Figure 1, following the equation proposed by [13]. 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 3, the algorithm performs the process for all requests that arrive in the network. The path is found in Line 4, and modulations are tested in the set of modulations for each core and slot. At the end, if a lightpath is found, it returns in Line 16, otherwise it will be empty.

The complexity of the Entrainer 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 $O(K \cdot V \cdot (V + E)logV)$. 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 Entrainer is $O(K \cdot V \cdot (V + E)logV)$.

IV. PERFORMANCE EVALUATION

This section presents the metrics evaluated in the work, discusses the relevance of each one, and presents the results of the proposed and compared algorithms.

We used the Flexgridsim simulator for performing the network flow [14]. It is specifically designed for Elastic Optical Networks with support to spatial dimension by using multiple cores, and also adapted for Data Center Network in this study.

The authors in [13] address the problem of spectrum fragmentation as the main element. Using a strategy based on spectrum slicing, they propose an algorithm that we will call Fragmentation. The main idea is to evaluate certain aspects by assigning weights to them, trying to find an efficient trade off and find the most appropriate route with low fragmentation. The work does not address specific data center traffic or consider multiple cores.

The authors in [15] consider the critical problem of connection failure due to disasters in an Elastic Optical Data Center Networks (EO-DCNs) scenario. The authors' proposal allocates primary resources for data transmission, as well as backup routes to ensure protection and survival. They evaluate the proposal, which we will call DataCenter, by comparing it to Integer Linear Programming models. This model does
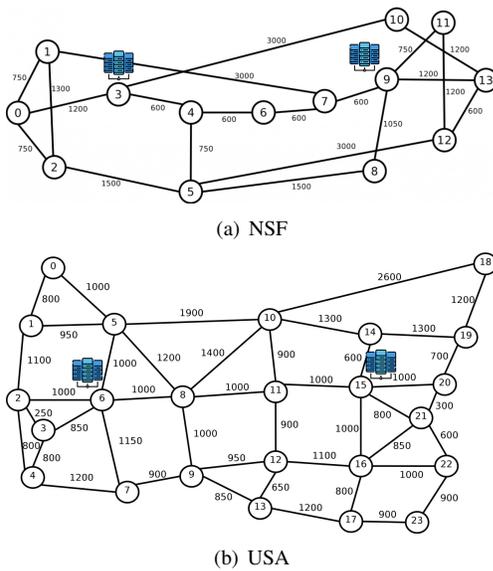

(a) NSF

(b) USA

Fig. 1. Topologies and network model.

Algorithm 1: Entrainer

input : Sets of Vertices, Links, Cores, Slots, Requests
output: Lightpath for DC-Node connections

1 Read network topology $Vertices$ and $Edges$
2 $Datacenter\_positioning(dc = 2)$
3 **for** *all* $r(source, destination, bandwidth) \in Requests$ **do**
4 Find set of $Paths$
5 **for** *all* $p \in Paths$ **do**
6   Calculate modulation level $m \in Modulations$ according to the distance
7   Calculate how many slots it will need to allocate the $bandwidth$ after applying modulation bw_m
8   **for** *all* $l \in Links$ **do**
9   **for** *all* $c \in Cores$ **do**
10   **for** *all* $s \in Slots$ **do**
11   **if** *all* $s\_index + bw_m$ *slots are free* **then**
12   Measurements of $crosstalk$ and $fragmentation$
13   Allocate (c, s)
14   **end**
15   **end**
16   **end**
17 **end**
18 **end**
19 **return** $lightpath(c, s, bw_m)$
20 **end**

not consider multiple cores, nor does it consider spectrum allocation in order to reduce fragmentation.

A. Metrics

To analyze the performance of our algorithm, we used the following metrics: Blocking Bandwidth Ratio (BBR), Crosstalk per Slot (CpS), Energy Efficiency (EE), Fragmentation Ratio (FR), and Data Transmitted (DT).

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

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. $\text{BW}_{\text{blocked}}(i)$ denotes the bandwidth blocked for request i, and $\text{BW}_{\text{request}}(j)$ 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.

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

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.

$$DT = \sum_{i=1}^{n} \text{BW}_{\text{transmitted}}(i) \cdot T(i) \tag{5}$$

The *DT* represents the total data sent through the network. In Equation 5, $\text{BW}_{\text{transmitted}}(i)$ is the bandwidth transmitted for each request i, and $T(i)$ is the time duration for which that bandwidth was utilized.

B. Results

In this section, the results are presented and discussed for the simulated topologies. The NSF topology 1(a) has 14 nodes and 20 links, with little connectivity and a more horizontal direction of communication. The USA topology 1(b) has 24 nodes and 43 communication links, with high connectivity.
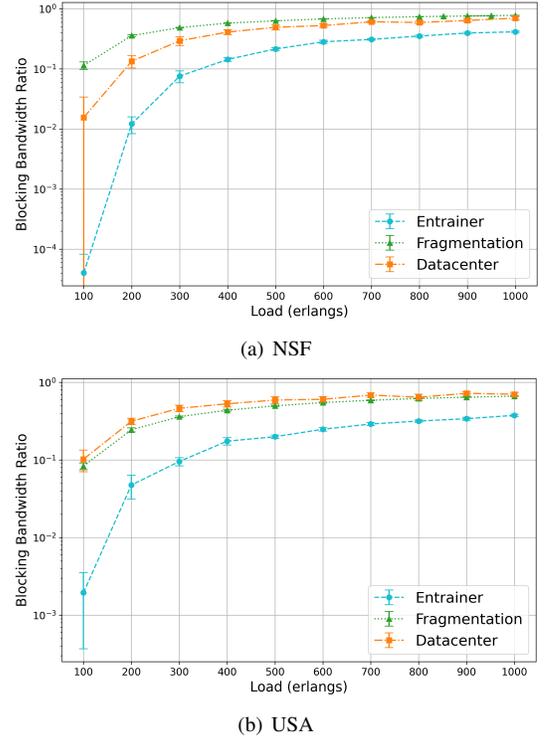

(a) NSF

(b) USA

Fig. 2. Blocking Bandwidth Ratio

Figure 2 shows bandwidth blocking ratio results for the three algorithms simulated. The first Subfigure 2(a) shows results for the NSF topology, where the proposed Entrainer algorithm has two orders of magnitude fewer blockages than the DataCenter algorithm, and up to three orders of magnitude fewer blockages than Fragmentation under lower loads. Throughout the simulated interval, Entrainer showed less blocking, while they were close to each other around the load of 500 Erlangs. For the USA topology (Subfigure 2(b)), Entrainer showed less blocking than algorithms compared by almost two orders of magnitude. The DataCenter and Fragmentation algorithms showed very close results, with DataCenter blocking more requests. The Fragmentation algorithm has a higher number of blocks because fragmentation is a priority element in the allocation, so the routing policy

becomes a secondary element in the decision-making process. The DataCenter algorithm concentrates transmission in more central nodes of the network, consequently generating congestion on certain links and making allocation more difficult.
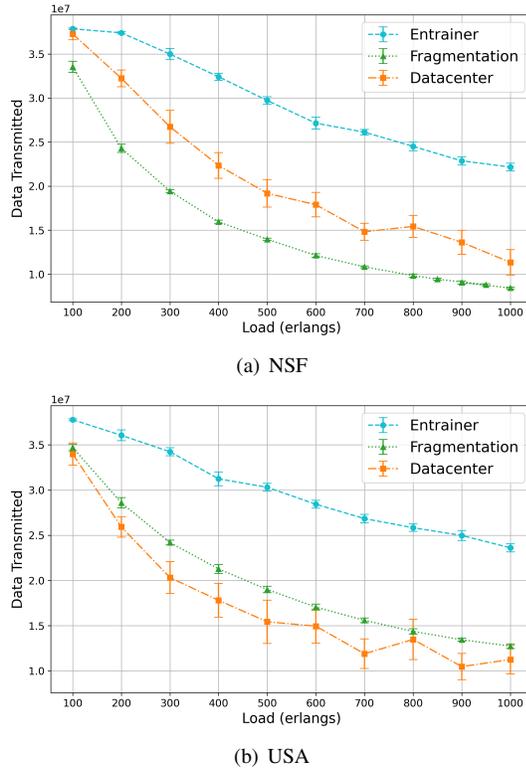

(a) NSF

(b) USA

Fig. 3. Data transmitted

Figure 3 shows the results of data transmitted over the network by the three algorithms simulated for two topologies. The Entrainer algorithm has the best performance in data transmitted over the network than the other algorithms, because it blocks fewer requests. In the NSF and USA topologies, the result is very close, with 2.5 Gbps of proximity, two more transmitted at higher loads than the compared algorithms, translating into a use of modulation that increases network capacity. For the NSF topology, the DataCenter algorithm has the second lowest result with a result close to 1.3 Gbps in 1000 erlangs. The Fragmentation algorithm shows the worst result over the loads. For USA, the Fragmentation and DataCenter algorithms invert their results over the loads but are similar at 1000 erlangs.

Figure 4 shows the performance of the three algorithms for energy efficiency in the two simulated topologies. The DataCenter algorithm has the highest energy efficiency, although it does not accept as many requests as the others, i.e. although it rejects many calls, it efficiently allocates the 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
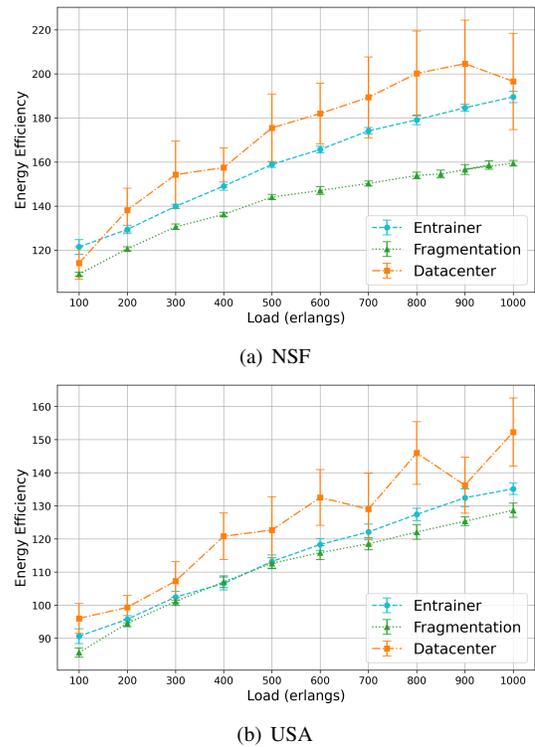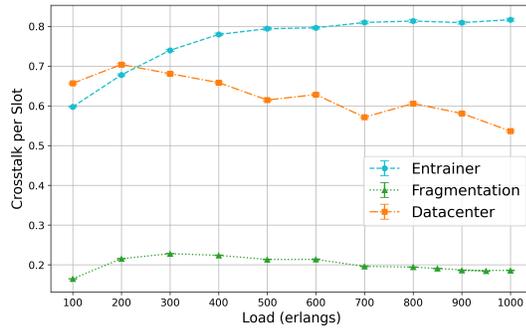

(a) NSF

(b) USA

Fig. 4. Energy Efficiency

NSF topology does not allow modulations with a higher transfer rate to be applied many times due to the length of the links. The Fragmentation algorithm is less energy-efficient because it allocates the spectrum in such a way as to prioritize the reduction of fragmentation, which can lead to the use of other link cores, increasing energy consumption.

Figure 5 shows the results for Crosstalk per Slot. The Proposed algorithm has higher Crosstalk per Slot because it allocates 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.

V. Conclusions

In this work, we propose an algorithm that allocates resources to requests, while also allowing concurrent allocation of communications between data centers. Combining the technologies of Elastic Optical Networks and Space-Division Multiplexing architecture has recently prompted several studies, indicating the prospect of relying on this model for optical core communication. The allocation, however, is complex due to the number of aspects to be considered. Our approach proposes a broader scenario, with data center and non-data center. Entrainer handles the communication and allocate the necessary resources, delivering as many calls as possible.
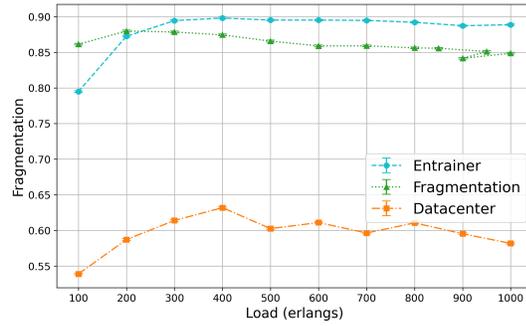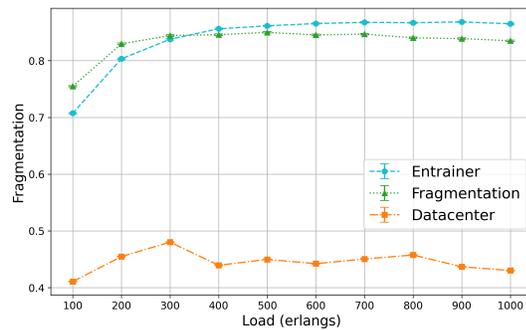
(a) NSF
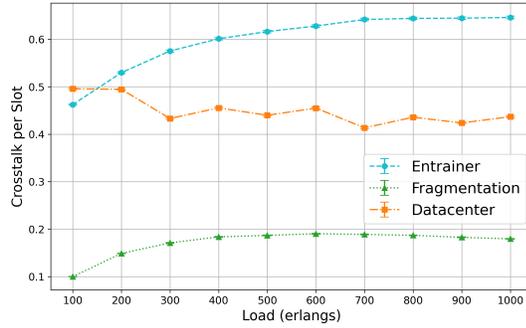
(b) USA

Fig. 5. Crosstalk per Slot

(a) NSF

(b) USA

Fig. 6. Fragmentation

There is room for further research that makes a more expressive analysis within the context of data centers and

targeted metrics. In addition, use machine learning techniques to solve the resource allocation problem. In terms of communication survival strategies, the study of disaster scenarios and more in-depth analysis of communication data centers can be addressed.

REFERENCES

[1] T. Panayiotou, M. Michalopoulou, and G. Ellinas, "Survey on machine learning for traffic-driven service provisioning in optical networks," *IEEE Communications Surveys Tutorials*, vol. 25, no. 2, pp. 1412–1443, 2023.

[2] S. Hosseini, I. de Miguel, N. Merayo, R. de la Rosa, R. M. Lorenzo, and R. J. Durán Barroso, "Energy efficient multipath routing in space division multiplexed elastic optical networks," *Computer Networks*, vol. 244, p. 110349, 2024.

[3] L. Liu, B. Chen, W. Ma, H. Chen, M. Gao, W. Shao, J. Wu, L. Peng, and P.-H. Ho, "Selective resource offloading in cloud-edge elastic optical networks," *Journal of Lightwave Technology*, vol. 41, no. 20, pp. 6431–6445, 2023.

[4] H. Aida and H. Uenohara, "Low-latency optical switching technology for next-generation edge-cloud computing platforms," *Opt. Continuum*, vol. 3, no. 6, pp. 970–982, Jun 2024.

[5] Sudhakar, A. M. Khan, and D. Batham, "Future generation elastic optical networks: A state-of-art review," in *Data Science and Applications*, S. J. Nanda, R. P. Yadav, A. H. Gandomi, and M. Saraswat, Eds. Singapore: Springer Nature Singapore, 2024, pp. 397–410.

[6] S. Behera, G. Savva, K. Manousakis, and G. Ellinas, "Impairment-aware routing, modulation, spectrum, and core allocation with bit loading in spectrally–spatially flexible optical networks," *J. Opt. Commun. Netw.*, vol. 15, no. 6, pp. 318–332, Jun 2023.

[7] A. Rezaee, R. McCann, and V. M. Vokkarane, "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)*, 2024, pp. 76–81.

[8] B. Chen, Y. Lei, J. Hu, L. Liu, W. Ma, J. Wu, M. Gao, W. Shao, and P.-H. Ho, "Crosstalk-sensitive core and spectrum assignment in mcf-based sdm-eons," *IEEE Transactions on Communications*, vol. 71, no. 12, pp. 7133–7148, 2023.

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

[10] A. Asiri and B. Wang, "Deep reinforcement learning for qot-aware routing, modulation, and spectrum assignment in elastic optical networks," *Journal of Lightwave Technology*, pp. 1–27, 2024.

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

[12] B. Chen, L. Liu, Y. Fan, W. Shao, M. Gao, H. Chen, W. Ju, P.-H. Ho, J. P. Jue, and G. Shen, "Low-latency partial resource offloading in cloud-edge elastic optical networks," *J. Opt. Commun. Netw.*, vol. 16, no. 2, pp. 142–158, Feb 2024. [Online]. Available: https://opg.optica.org/jocn/abstract.cfm?URI=jocn-16-2-142

[13] M. Ju, Y. Liu, F. Zhou, and S. Xiao, "Disaster-resilient and distance-adaptive services provisioning in elastic optical inter-data center networks," *Journal of Lightwave Technology*, vol. 40, no. 13, pp. 4064–4077, 2022.

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

[15] "Spectrum slicing-based fragmentation aware routing and spectrum allocation in elastic optical networks," *Optical Switching and Networking*, vol. 45, p. 100673, 2022.