# Efficient Traffic Allocation Algorithms for Enhancing Data Center Performance in Elastic Optical Networks with Space Division Multiplexing

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***Abstract.*** *Recent emerging services have reshaped the paradigm of network organization and content delivery. In this context, users generate increasingly heterogeneous traffic while delegating processing tasks to large data centers located at the network core. The resulting growth in data exchange among core network elements demands high transmission rates and efficient resource utilization, requirements addressed by the SDM-DC-EON architecture. Nevertheless, effective resource management mechanisms are still necessary to ensure that service requirements are met. To this end, this master's master's thesis proposes three routing algorithms designed for the aforementioned architecture. The proposed solutions achieve performance comparable to existing approaches in the literature, while delivering superior results, particularly with respect to the Bandwidth Blocking Ratio, which directly reflects the number of successfully established network connections.*

## 1. Introduction

Global communications are developing rapidly, both in terms of technology and the volume of data transmitted. Digital services such as video streaming, Internet of Things (IoT), and cloud services are primarily responsible for changes in traffic patterns. As a result, new demands are exposing specific weaknesses in the current network infrastructure, which is operating close to its limits [Hosseini et al. 2024]. The cloud services model has changed the paradigm of communication and data transmission, enabling a wide range of uses, from massive data storage to real-time data processing. This model highlights the need for new mechanisms and infrastructure capable of meeting the high-speed, high-capacity requirements [Rezaee et al. 2024].

Traditional infrastructure uses Wavelength-Division Multiplexing (WDM) technology at the network core, characterized by its rigid distribution of optical resources. The optical spectrum is poorly fragmented, creating challenges for meeting modern transmission needs. To combat these limitations, Elastic Optical Networks (EON) have emerged, with a more granular spectrum grid that adapts more closely to heterogeneous traffic [Rezaee et al. 2024]. To mitigate these challenges arising from the EON, the Routing and Spectrum Assignment (RSA) algorithms address the resource allocation problem.

In addition to the need for flexible links, improving the network's physical layer is essential to enhancing the overall performance. This area's advancement can lead to substantial gains in speed, capacity, and resilience. By integrating spectrally and spatially flexible links into the physical layer, networks can dynamically adjust to the fluctuating demands of different applications by adding a spatial dimension with Multicore Fiber (MCF) [Rezaee et al. 2024].This flexibility allows mechanisms to allocate network resources more efficiently, optimizing data transmission and reducing bottlenecks in Space-Division Multiplexing Elastic Optical Networks (SDM-EON).

In addition to routing and spectrum allocation, two problems arise from this architecture: Crosstalk (XT) and spectrum Fragmentation [Rezaee et al. 2024]. The XT is an interference caused by adjacent cores when two or more transmissions occupy the same frequency band simultaneously. This interference may degrade other transmissions, making communication impossible. The fragmentation occurs over time, creating small gaps in the spectrum that do not fit new demands. Another attempt to improve capacity is to apply modulations to the transmission. The selected modulation level affects the maximum signal distance and the acceptable interference limit. Combining these aspects yields the Routing, Modulation, Spectrum, and Core Assignment (RMLSCA) problem.

## 2. Related Works

To manage the intense data exchanges on the SDM-EON, the authors presented a new dynamic routing algorithm. It uses a multipath strategy to reduce the probability of blocking and energy consumption [Hosseini et al. 2024]. Multipath uses the same route for both paths to mitigate differential delay. In addition, crosstalk and fragmentation constraints are respected, with adaptive modulation added. However, there is no different treatment for volumes generated by data centers.

This paper presents a new meta-heuristic approach using Genetic Algorithm (GA) [Agarwal and Bhatia 2024]. The authors evaluate the efficiency of singlepath and multipath allocation policies. The algorithm seeks to reduce the probability of bandwidth blocking by finding the optimal solution. In this context, the work does not differentiate between data center traffic and does not address physical-layer challenges. To mitigate intercore crosstalk, the study presented a routing algorithm that incorporates XT-aware policies [Rezaee et al. 2024]. Two policies are defined based on the network's crosstalk values, and then a bandwidth-slicing technique is used to allocate spectrum efficiently. The algorithm seeks to maintain adequate crosstalk levels while providing more allocations through spectrum fragmentation management, without including specific strategies for cloud-based traffic.

The authors proposed a new routing algorithm for natural disaster scenarios with disrupted infrastructure [Zou et al. 2024]. A set of Virtual Network Functions (VNFs) is restored, so the network returns to its fully operational state. In the Data Center Elastic Optical Network (DC-EON), the recovery mechanism must act quickly, given the volume of data transmitted, as delays can degrade the user experience. The authors proposed a new task offloading mechanism to reduce latency in critical applications. This task involves deciding whether to move the user to another point in the Cloud-Edge Elastic Optical Network (CE-EON) [Chen et al. 2024]. A proposed Integer Linear Programming (ILP) model is the baseline for other heuristic solutions that perform partial offloading. The results point to the effectiveness of the Proportional Segment Approach mechanism for reducing E2E latency, with a low probability of blocking in dynamic scenarios.

**Table 1. Comparison table between proposals in the literature.**

| Literature | SDM | Crosstalk | Spectrum Efficiency | Data Center |
|---|---|---|---|---|
| [Hosseini et al. 2024] | ✓ | ✓ | ✓ | |
| [Agarwal and Bhatia 2024] | | | ✓ | |
| [Rezaee et al. 2024] | ✓ | ✓ | ✓ | |
| [Zou et al. 2024] | | | ✓ | ✓ |
| [Chen et al. 2024] | | | ✓ | ✓ |
| Entrainer (Algorithm 1) | ✓ | ✓ | ✓ | ✓ |
| Redeclare (Algorithm 2) | ✓ | ✓ | ✓ | ✓ |
| Centerclare (Algorithm 3 ) | ✓ | ✓ | ✓ | ✓ |

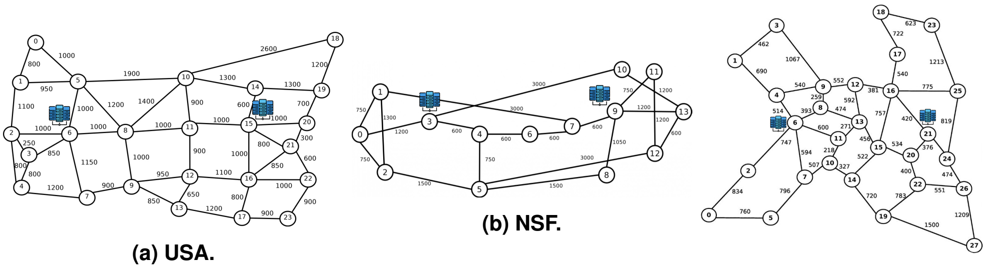
## 3. Network Scenario

This master's thesis considers the Space Division Multiplexing Data Center Elastic Optical Networks (SDM-DC-EON) for the transmission of dynamic traffic. The highlight of this model is the improvements the technologies enable. The network uses Spatially Flexible Reconfigurable Optical Add/Drop Multiplexers (SF-ROADM) to support dynamic routing, through wavelength-selective switching and space-wavelength granularity. Optical Cross-Connects (OXC) allow flexible allocation across multiple channels transmitted over several fiber cores or modes. At another level of transmission are Multiple-Input Multiple-Output (MIMO) processing units, which aim to improve transmission efficiency by mitigating crosstalk and optimizing signal recovery after spatial multiplexing. For the transmitted optical signal, we deploy Multi-Flow Transponders (MFT) to split it into multiple sub-transponders that dynamically allocate bandwidth. To compensate for signal loss propagation, we use Multi-Core Erbium-Doped Fiber Amplifiers (MC-EDFA) to maintain signal integrity along the path.

The topologies in Figure 1 consist of bidirectional fibers containing seven cores arranged in a hexagonal pattern with one central core. Each core has a transmission spectrum divided into 320 slots, capable of operating over a 12.5 GHz bandwidth. The equipment used does not allow exchanging cores for the same transmission, and the slots used for a single transmission must be continuous. Also, adaptive modulation allows transmission up to six times more bits per symbol. However, modulation selection must follow constraints, such as the total transmission distance and physical interference (e.g., crosstalk), to avoid signal degradation that renders decoding at the destination node unfeasible. The available modulations are BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, and 64-QAM (1 to 6 bits per symbol, respectively).

### 3.1. Metodology

To evaluate the three algorithms, the Flexgridsim discrete event network simulator was used [Moura and Drummond 2020]. We generated a set of requests with source and destination nodes from a Poisson process and distributed uniformly across pairs, with 30% of the events characterized for data center communication. We performed 10 replicates at loads ranging from 100 to 1000 Erlangs, with a 95% confidence interval. Each round had 100,000 requests and a bandwidth of 25/50/125/200/500/750/1000 Gbps. We used two algorithms found in the literature as a basis for comparison: **Datacenter** [Ju et al. 2022] and **Fragmentation** [Liu et al. 2022]. The Datacenter algorithm performs optical resource



**(a) USA.** **(b) NSF.** **(c) PAN.**

**Figure 1. Topologies.**

provisioning in Elastic Optical Data Center Networks model during a disaster. This work prioritizes delivering content from data centers and provides resilience mechanisms so that the nearest data center can fulfill the request. The Fragmentation algorithm proposes slicing the network in the EON architecture while relaxing the contiguity constraint to reduce spectrum fragmentation, allowing reactive organization of transmissions.

We used the following metrics to evaluate the performance of both algorithms: Bandwidth Blocking Ratio (BBR), the sum of all blocked requests divided by the total number of requests; Crosstalk per Slot (XTPS), the result of dividing the number of slots allocated on the same frequency by the total number of slots on the same link, calculated at time intervals; Energy Efficiency (EE), the sum of all transmitted bandwidth divided by energy expenditure; Average Number of Hops (AVGH), the average number of hops for all transmissions. Fragmentation Ratio (FR), the division of the largest set of contiguous slots by the number of slots available in the core; Average Bits per Second (AVGBPS), the average bandwidth in Gbps transmitted; Power Consumption (PC) is the total energy consumed for transmission; Data Transmitted (DT), the total data transmitted by all transmissions; Data Center Blocked (DCB) is the ratio between blocked data center transmissions and the total number of transmissions.

## 4. Algorithms

This section presents the three routing algorithms for the SDM-DC-EON architecture proposed in the master's thesis, along with the simulation results. We compared the results with two other algorithms from the literature and discussed them.

### 4.1. Entrainer's Functions

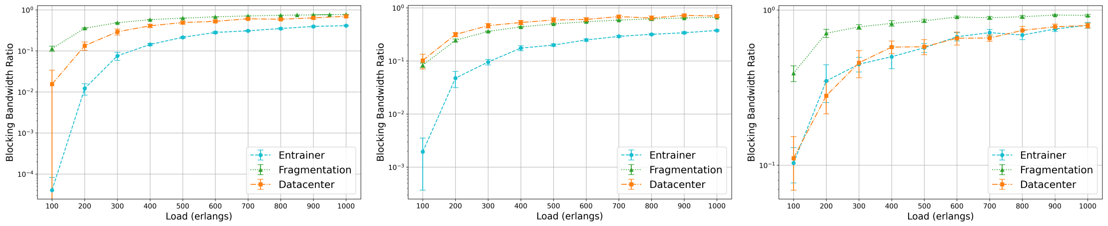
The Entrainer is described in Algorithm 1. In Line 1, the algorithm maps the network and its resources. Then, in Line 2, it positions two data centers at network nodes based on the topology's interconnection, with a relaxation relative to the original algorithm [Ju et al. 2022]. In Line 3, the algorithm begins the allocation process for each request. In Line 4, the algorithm finds a set of 5 paths ordered by transmission distance. In Line 5, the algorithm performs modulation by distance and calculates the number of slots required (Lines 6 and 7). For each route link, the algorithm checks the available spectrum in cores and slots (Lines 8–11). To reduce fragmentation and crosstalk, the outer cores with the lowest index are prioritized (Line 12). In Line 13, if the spectrum is available, resources are allocated. Otherwise (Line 14), the following path is tested until all paths are exhausted. The result is the set of optical resources called a lightpath (Line 20). The complexity of the Entrainer algorithm is analyzed as follows. The complexity of mapping the network is $O(V + E)$, where $V$ is the set of vertices and $E$ is the set of edges. To find the path, we consider Yen's algorithm, which has complexity $O(K * V * (V + E)logV)$. 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 $O(K * V * (V + E)logV)$.

**Algorithm 1:** ENTRAINER

```
Input  : Sets of Vertices ($V$), Links ($L$), Cores ($C$), Slots ($S$), Requests ($R$)
Output: Lightpath for DC-Node connections
Read network topology $G = (V, E)$;
$Datacenter\_positioning$ ($dc = 2$);
for $r(src, dst, bw) \in R$ do
    Find set of Paths $P$;
    for $p \in P$ do
        Calculate modulation level $m \in Modulations$ according to the distance;
        Calculate number of slots after applying $bw_m$;
        for $l \in L$ do
            for $c \in C$ do
                for $s \in S$ do
                    if $all\ s_{index} + bw_m\ slots\ are\ available$ then
                        Measurement of $crosstalk$ and $fragmentation$;
                        Reserve $(c, s)$;
                        return $lightpath(c, s, bw_{mod})$;
    Block Request and return;
```

### 4.1.1. Results

Figure 2 shows BBR results for Entrainer, Fragmentation, and Datacenter algorithms. Entrainer outperforms during all load intervals up to three (NSF Figure 2a), two (USA Figure 2b), and one (PAN Figure 2c) orders of magnitude. Fragmentation prioritizes fragmentation policies in allocation, so routing is secondary in decision-making process. While Datacenter concentrates in allocate data center traffic without impact on others transmissions, however saturating specific links and making allocation more complex.



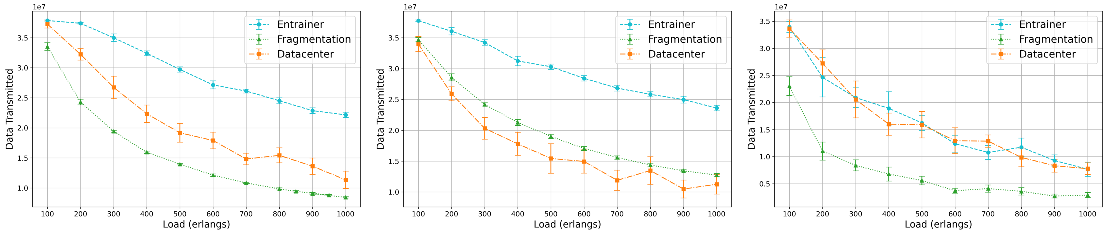
(a) NSF Topology.

(b) USA Topology.

(c) PAN Topology.

**Figure 2. Bandwidth Blocking Ratio.**

Figure 3 shows DT over the network. Entrainer blocks fewer requests, i.e. it transmits more data. For NSF 3a and USA 3b, results are up to two orders of magnitude greater than Fragmentation and Datacenter. For PAN 3c, Entrainer is closer to Datacenter due to connectivity, that allows more transmissions. For the NSF, Datacenter has the second lowest result at 1.3 Gbps in 1000 erlangs. Fragmentation shows the worst result over the simulation. For USA, Fragmentation and Datacenter invert results along the loads but are similar at 1000 erlangs. For PAN, Fragmentation transmits less data due to its policy of prioritize reducing fragmentation over other metrics.



**(a) NSF Topology.** **(b) USA Topology.** **(c) PAN Topology.**

**Figure 3. Data Transmitted.**

### 4.2. Redeclare's Functions

The Algorithm 2 describes 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 present Figures 1a, 1b, 1c, following the equation proposed by [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 3, the algorithm performs the process for all requests that arrival in the network. A set of paths is found in Line 4, and for each path in the set (Line 5), a modulation level is selected based on the lenght in $km$ of all links (Line 6). The algorithms check availability of resource in the spectrum matrix (core x slot) of each link (Line 7 - 10). Then, it measures the $XT$ and fragmentation (Line 11) and it allocates the resource in Line 12. In case it does not found resources, the algorithms returns empty, otherwise it returns a lightpath with resources (Line 19). 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 $O(K * V * (V + E)logV)$. 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 $O(K * V * (V + E)logV)$.

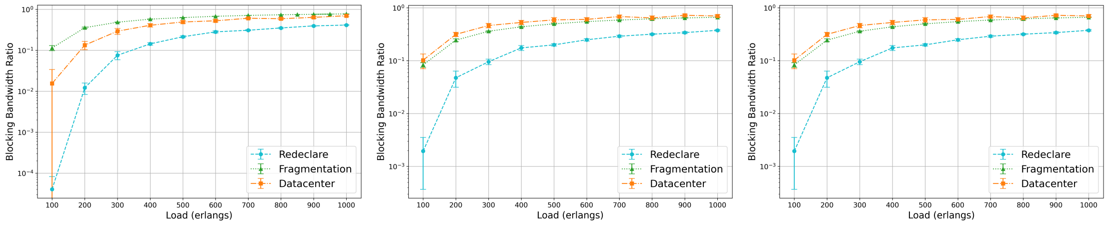
#### 4.2.1. Results

Figure 4 shows BBR results. For NSF, Redeclare has up to three orders of magnitude less blocking. Datacenter and Fragmentation had similar results, while Redeclare showed less blocking for the USA topology. For PAN, Redeclare outperforms Datacenter at 400 Erlangs and higher. Fragmentation considers the core fragmentation level as the principal

**Algorithm 2:** REDECLARE

```
Input  : Topology $G(V, L)$, Set of Cores $C$, Slot Matrix $S$, Request Set $R$
Output: Assignment $(p, c, s)$ or Blocked Request
Pre-compute $Datacenter\_Nodes$ ($dc = 2$);
Map available network state;
for each incoming request $r(s, d, bw) \in R$ do
    Define candidate path set $P_{sd}$ using shortest-path metrics;
    for path $p \in P_{sd}$ do
        Estimate modulation $m$ based on optical reach of $p$;
        Calculate slot demand $\Delta s = \lceil bw/m \rceil + guardband$;
        for core $c \in C$ do
            for starting slot $s \in S$ do
                if contiguous slots $[s, s + \Delta s]$ are free on path $p$ and core $c$ then
                    Compute $XT$ (Crosstalk) and $F_{ext}$ (External Fragmentation);
                    if $XT < threshold$ then
                        Resource Reservation: Update $G$ with $(p, c, s, \Delta s)$;
                        return $Establish\_Lightpath(p, c, s)$;
    Block request and return;
```

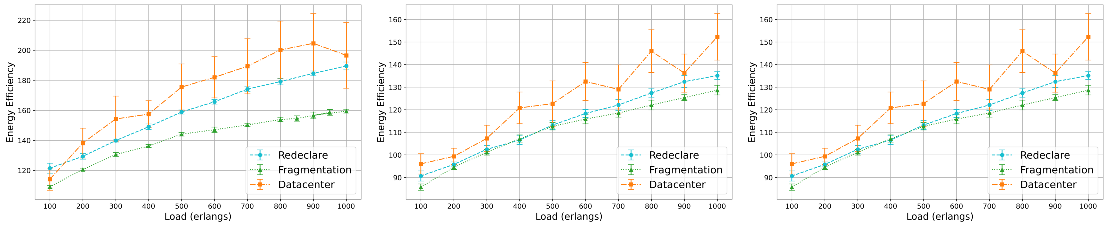
factor of its resource allocation policy. It means the route may not be optimal, leading to inefficient allocations. Congestion forms in the network's center, unbalancing resource use: some links saturate, while others become underused. This situation makes it challenging to allocate long-duration requests. Redeclare performs routing first, seeking to allocate the fewest resources (since more links mean more cores x slots). Then, among the smallest routes, it selects the one with the least impact on network fragmentation and crosstalk.



**(a) NSF Topology.** **(b) USA Topology.** **(c) PAN Topology.**

**Figure 4. Bandwidth Blocking Ratio.**

Figure 5 shows EE for both 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 Redeclare algorithm shows results between the other two compared, with a higher energy efficiency than Fragmentation, 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 fragmentation, which can lead to the use of other link cores, increasing energy consumption.



**(a) NSF Topology.** **(b) USA Topology.** **(c) PAN Topology.**

**Figure 5. Energy Efficiency.**

### 4.3. Centerclare's Functions

The operation of Centerclare is presented by Algorithm 3. The algorithm receives information from the network and maps it (Line 1). In Line 2, it positions two data centers in nodes with high interconnection in the topology. In Line 3, it reads the traffic and acts on each request individually. In Line 4, it finds the shortest paths and calculates the fragmentation and crosstalk levels (Lines 5-8). If the levels exceed the limits, the route is removed from the set (Lines 9-10). If the traffic is between data centers, the set of paths is inverted (Lines 13-14). The algorithm checks all links on the selected route (Line 16) and searches for available core and slot resources (Lines 17-19). When found, it returns the lightpath (Line 20). The process repeats until the lightpath is found or the set of paths is exhausted (Line 25). 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 $O(K * V * (V + E)logV)$. 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 $O(K * V * (V + E)logV)$.

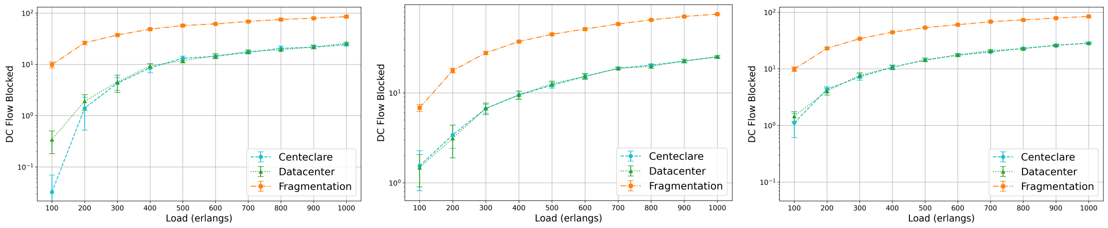
#### 4.3.1. Results

Figure 6 shows the amount of traffic blocked specifically when communicating between data centers. For both results (Figures 6a, 6b and 6c), 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.

Figure 7 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 XT values for both situations. Meanwhile, the algorithms with less blocking have a higher level of XT interference between cores. Thus, the Datacenter algorithm has values just above the Centerclare algorithm for the NSF topology (Figure 7a), while the two remain fairly close in the USA and PAN topologies (Figures 7b and 7c).

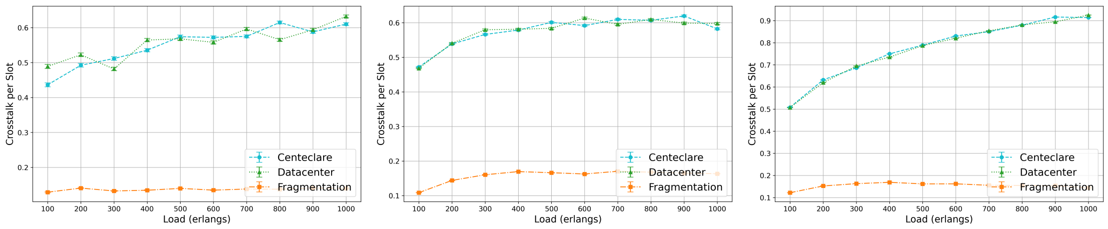
**Algorithm 3:** CENTERCLARE

```
Input  : Network Requests ($R$), Vertices ($V$), Links ($L$), Cores ($C$), Slots ($S$)
Output: Lightpath connections
Mapping network resources for allocation;
$Datacenter\_positioning$ ($dc = 2$);
for $r(src, dst, bw) \in R$ do
    Find set of shortest paths $P$;
    for $p \in P$ do
        Apply modulation according to distance;
        Compute Fragmentation $Frag$ level;
        Compute Crosstalk $XT$ Level;
        if $Frag\ or\ XT > threshold$ then
            Remove $p$ from $P$;
    if $r(src, dst, bw)\ is\ DC - to - DC$ then
        Invert the sequence of $P$;
    for $l \in L$ do
        for $c \in C$ do
            for $s \in S$ do
                if $(c, s) + bw_m\ slots\ not\ available$ then
                    continue;
                else
                    return $lightpath$;
    Block request and return;
```



**(a) NSF Topology.** **(b) USA Topology.** **(c) PAN Topology.**

**Figure 6. Data Center Traffic Blocked**



**(a) NSF Topology.** **(b) USA Topology.** **(c) PAN Topology.**

**Figure 7. Crosstalk per Slot Ratio**

## 5. Conclusions and Perspectives

This master's thesis developed three algorithms for managing optical resources in the SDM-DC-EON architecture, enabling high-speed, high-bandwidth services and evaluating network performance, particularly the impact of data center-to-data center transmissions on the network core. Resource management is handled during routing and allocation, treated here as a joint problem. The proposed algorithms improve network flow by addressing two key physical issues: spectrum fragmentation and crosstalk. Controlling these factors through monitoring and bounded operation is essential to support future connections and mitigate the impact of data center communications.

The research also highlights the need for new management mechanisms across multiple levels to maximize network flow. From an architectural perspective, this includes exploring intelligent allocation models. More advanced solutions are required to support reliable, high-availability data center communications, incorporating new metrics such as latency sensitivity. Therefore, resource allocation in SDM-DC-EON remains a complex problem requiring further investigation.

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## References

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

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.

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.

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, P. M. and Drummond, A. C. (2020). FlexGridSim: Flexible Grid Optical Network Simulator. http://www.lrc.ic.unicamp.br/FlexGridSim/.

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.

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.