

Resource Optimization in Elastic Optical Networks Using Threshold-Based Routing and Fragmentation-Aware Spectrum Allocation

Kamagaté Beman Hamidja¹, Kanga Koffi¹, Coulibaly Kpinan Tiekoura¹, Konaté Adama¹, Michel Babri²

¹Ecole Supérieure Africaine des Technologies de l'Information et de la Communication (ESATIC), LASTIC, Abidjan, Côte d'Ivoire

²UMRI MSN INPHB INP—Houphouët Boigny, Yamoussoukro, Côte d'Ivoire

Email: beman.kamagate@esatic.edu.ci

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Abstract

This paper proposes an efficient strategy for resource utilization in Elastic Optical Networks (EONs) to minimize spectrum fragmentation and reduce connection blocking probability during Routing and Spectrum Allocation (RSA). The proposed method, Dynamic Threshold-Based Routing and Spectrum Allocation with Fragmentation Awareness (DT-RSAF), integrates rerouting and spectrum defragmentation as needed. By leveraging Yen's shortest path algorithm, DT-RSAF enhances resource utilization while ensuring improved service continuity. A dynamic threshold mechanism enables the algorithm to adapt to varying network conditions, while its fragmentation awareness effectively mitigates spectrum fragmentation. Simulation results on NSFNET and COST 239 topologies demonstrate that DT-RSAF significantly outperforms methods such as K-Shortest Path Routing and Spectrum Allocation (KSP-RSA), Load Balanced and Fragmentation-Aware (LBFA), and the Invasive Weed Optimization-based RSA (IWO-RSA). Under heavy traffic, DT-RSAF reduces the blocking probability by up to 15% and achieves lower Bandwidth Fragmentation Ratios (BFR), ranging from 74% to 75%, compared to 77% - 80% for KSP-RSA, 75% - 77% for LBFA, and approximately 76% for IWO-RSA. DT-RSAF also demonstrated reasonable computation times compared to KSP-RSA, LBFA, and IWO-RSA. On a small-sized network, its computation time was 8710 times faster than that of Integer Linear Programming (ILP) on the same network topology. Additionally, it achieved a similar execution time to LBFA and outperformed IWO-RSA in terms of efficiency. These results highlight DT-RSAF's capability to maintain large contiguous frequency blocks, making it highly effective for accommodating high-bandwidth requests

in EONs while maintaining reasonable execution times.

Keywords

Elastic Optical Networks (EONs), Spectrum Fragmentation, Routing and Spectrum Allocation (RSA), Connection Rerouting, Heuristic

1. Introduction

With advances in information and communication technologies (ICT) [1], which have led to a global explosion in the volume of data exchanged, communication infrastructures must evolve to meet the ever-growing demand for bandwidth. Infrastructures such as data centers, cloud service providers, 5G networks, mobile backhaul, Internet Exchange Points (IXPs), and many others now place substantial demands on network capacity. Traditional Wavelength Division Multiplexing (WDM) optical networks, which operate on a fixed frequency grid, reveal significant limitations in terms of flexibility and efficiency [2].

In this context, Elastic Optical Networks (EONs) [2] have emerged as an essential and innovative solution. Unlike traditional optical networks that rely on a fixed grid with rigid channel spacing (e.g., 50 GHz or 100 GHz), Elastic Optical Networks (EONs) leverage a flexible grid that allows for variable channel widths and dynamic allocation of spectral resources tailored to the needs of each connection. The spectrum in EONs is divided into smaller units called frequency slots, typically measuring 12.5 GHz or 6.25 GHz. Connections can utilize a customizable number of slots based on their specific bandwidth requirements. EONs are designed to accommodate a wide range of services with diverse demands in latency, bandwidth, and quality of service. They can provide dedicated channels for critical applications, such as real-time communication, while optimizing resources for less demanding services. This adaptability in resource management enables EONs to reduce operational costs by minimizing the need for additional fiber optic installations or equipment upgrades. As a result, network operators can maximize the utilization of existing infrastructure while meeting the increasing demand for bandwidth [3].

Despite the flexibility in spectrum usage offered by EONs, Routing and Spectrum Allocation (RSA), which involves determining optimal routes for data transmission and assigning frequency slots to these routes, remains a critical challenge in Elastic Optical Networks [4]. RSA specifies how connections (traffic demands) are established by selecting paths through the network and allocating the required frequency slots along those paths. The RSA process must comply with two key constraints: spectrum continuity, which ensures the same frequency slots are available across all links in the chosen path, and spectrum contiguity, which requires the allocated slots to be adjacent in the spectrum [4]. This process is inherently more complex in EONs compared to traditional optical networks, primarily

due to their flexible-grid architecture, which enables the dynamic allocation of spectral resources. If this process lacks efficiency, it may lead to spectrum fragmentation and a high likelihood of connection blockages, even with the flexible grid of EON. Spectrum fragmentation results in inefficient resource use, diminished network capacity, and a higher blocking probability for incoming traffic, ultimately preventing the network from fully leveraging its available spectrum resources [5].

In this work, an optimal routing and spectrum allocation strategy is proposed based on continuous monitoring of the network status. This approach observes key metrics such as spectrum usage, blocking probability, and spectrum fragmentation. By harnessing this data, it facilitates efficient resource assignment, reducing spectrum fragmentation and blocking probability while improving overall spectrum utilization.

The remainder of this paper is organized as follows: Section 2 offers a detailed review of related work on routing and spectrum allocation methods, focusing on existing strategies. Section 3 introduces our proposed method, which combines the Best-Fit heuristic with selective rerouting and a dynamic threshold to optimize resource management in EONs. This section also outlines the experimental and simulation framework employed for evaluation. Section 4 presents the results and discussion, featuring a performance analysis and comparisons with alternative approaches. Lastly, Section 5 concludes with a summary of our key findings.

2. Related Works

In elastic optical networks (EONs), the fundamental problem of Routing and Spectrum Allocation (RSA) relies on two main tasks [6] which are routing and spectrum allocation.

The task of routing consists of determining the physical path that data will take across the network, from the source node to the destination node. The routing process considers the network's topology and aims to select a path that is efficient and meets the service requirements while avoiding congested or unavailable links.

Several routing techniques are commonly employed. Shortest Path Routing (SPR) is one such method, which selects the path with the fewest steps or the shortest distance. Another approach is load-balancing routing, which distributes traffic across the network to avoid overloading any single area. Adaptive routing is also used. It dynamically adjusts paths based on factors such as network congestion or the availability of resources, helping maintain efficient data flow [7].

As for the task of spectrum allocation, it involves assigning an appropriate range of frequency slots along the selected path for each data request. EONs allow for flexible spectrum allocation, which can be adjusted according to bandwidth needs. Spectrum allocation strategies include First-Fit (FF), which assigns the first available continuous block of spectrum that meets the request; Best-Fit (BF), which finds the smallest available spectrum block that can accommodate the request; and Exact-Fit (EF), which assigns precisely the amount of spectrum

required, particularly effective in managing high-demand traffic [8].

Routing and spectrum allocation can be represented as an Integer Linear Programming (ILP) problem, which may require significant computational time to solve [9]. To reduce computational time, several studies make use of heuristics and metaheuristics.

Among them, work in [10] presents a method called Load-Balanced and Fragmentation-Aware (LBFA) to address routing and spectrum allocation in optical networks. This method combines load-balanced routing with spectrum allocation to reduce fragmentation. It operates by selecting the least congested path for each connection request in real-time, based on network load data, thereby reducing congestion by distributing connections across less saturated links. Although LBFA adapts well to varying traffic demands, it requires continuous load evaluation and precise fragmentation management. Another heuristic approach is presented in [11], where an energy-efficient algorithm is applied for multipath routing, modulation, and spectrum assignment. This heuristic aims to reduce blocking probability and conserve energy by optimizing routing and spectrum allocation. It employs a best-fit heuristic for resource allocation, prioritizing exact-fit slots while ensuring continuity constraints. Additionally, it dynamically adjusts resource allocation to respond to traffic fluctuations as connections are established and terminated. While the algorithm demonstrates high performance, its effectiveness may vary depending on network link lengths, showing optimal results in networks with longer links that require more robust modulation formats.

The study in [12] explores the challenges of spectrum fragmentation in multi-band elastic optical networks based on another heuristic. The authors developed a resilient routing, band, modulation, and spectrum allocation algorithm. Their method incorporates shared backup path protection and a band partitioning strategy, assigning one band to the primary path and another band to the backup path. This structure seeks to reduce spectrum fragmentation by utilizing metrics that consider both shared and available resources. The findings indicate that the algorithm effectively lowers blocking and fragmentation rates while enhancing the optical signal to noise ratio.

The paper [13] addresses the problem of spectrum fragmentation in semi-filterless elastic optical networks, a challenge intensified by the increase in network capacity with the introduction of the L band, which degrades transmission quality and raises the bandwidth blocking rate. To tackle this issue, the authors propose a routing, modulation, and spectrum assignment algorithm with three specific innovations: the K-Shortest-Subnet-Paths (KSSP) algorithm to identify candidate paths, a Load-Balancing Least-Resources (LBLR) policy to reorder these paths, and the Maximum Occupied Neighbors (MON) rule to assign spectrum resources. This method stands out for its ability to reduce blocking rates by optimizing resource usage.

Others studies use metaheuristics for routing and spectrum allocation. Among them, the study presented in [14] tackles the challenge RSA in elastic optical

networks, by using a metaheuristic built on a genetic algorithm. It adjusts the RSA strategy for each source-destination pair, selecting between two processing sequences: routing before spectrum assignment (R-SA) or spectrum assignment before routing (SA-R). This adaptable approach enables enhanced overall performance by combining the strengths of both methods. A key innovation of this methodology is its ability to tailor the allocation strategy to the unique characteristics of each source-destination pair, which proves especially beneficial across diverse network topologies. Simulation results demonstrate that this strategy significantly lowers the blocking probability compared to using only the R-SA or SA-R approaches and also improves load distribution and spectrum compactness. This approach offers benefits such as reduced blocking probability and more efficient network resource management.

The works [15] presents another metaheuristic algorithm designed for traffic and fragmentation management in routing and spectrum assignment within elastic optical networks. This algorithm addresses the challenges of dynamic traffic demands and spectrum fragmentation through a blend of two metaheuristic approaches: Invasive Weed Optimization (IWO) for RSA and the Spotted Hyena Optimizer (SHO) for defragmenting the spectrum. Together, these metaheuristics improve spectrum efficiency by creating contiguous free slots, reducing fragmentation, and lowering blocking probabilities. However, the IWO-RSA and SHO algorithms are computationally complex, particularly in large and dynamic networks, which may impede real-time processing.

Given the challenges outlined, the proposed RSA methods focus on reducing blocking rates and spectrum fragmentation while enhancing resource utilization. However, these benefits often come at the expense of increased computational demands, particularly for methods relying on metaheuristics. Furthermore, while effective in stable traffic conditions, some of these methods struggle to adapt to dynamic demand fluctuations. To address these limitations, we propose a heuristic approach that integrates spectrum and path reorganization for selected active connections with an optimal allocation strategy to efficiently manage new connection requests. This approach leverages continuous network monitoring, enabling seamless rerouting followed by defragmentation of active connections prioritized by bandwidth requirements whenever a predefined threshold is exceeded.

3. Materials and Method

3.1. Elastic Optical Network Resources

The optical spectrum is divided into segments known as slices or frequency slots. Each frequency slot is conceptually represented by an integer index ranging from 1 to a maximum value, determined by the width of the optical spectrum. **Figure 1** illustrates the division of a section of the optical spectrum into 10 frequency slots, numbered from 1 to 10 along two links. For example, as depicted in **Figure 1**, if a traffic demand requires only one frequency slot, the connection could be established using slot 1 on both links 1 and 2. However, slot 2 would not be suitable

due to the current configuration: while slot 2 is available on link 1, it is already occupied on link 2. The allocation of required frequency slots to a set of connections must respect two constraints: continuity and contiguity.

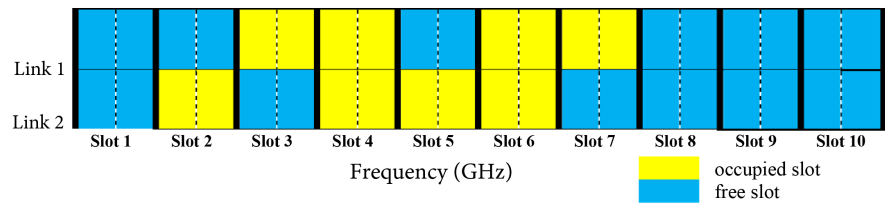


Figure 1. Frequency slots in elastic optical network.

In EON, the continuity constraint refers to the requirement that a connection (lightpath) must use the same frequency slots across all the optical links it traverses. This ensures that the optical signal remains uninterrupted and consistent throughout its path. Without this constraint, a connection may experience signal degradation or failure due to mismatched frequency slots on different links. **Figure 2** illustrates a three-node linear network (Node A → Node B → Node C). Frequency slots are represented as rectangles above each link. Slots 3 to 5 are highlighted in the same color across Link 1 and Link 2, demonstrating the continuity constraint.

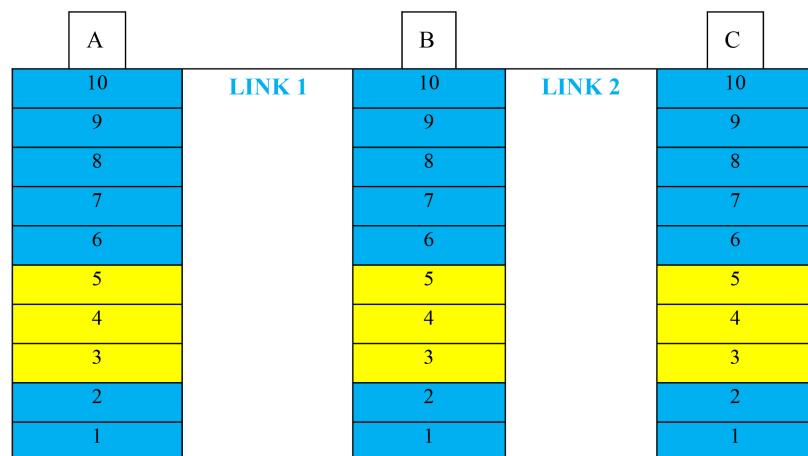


Figure 2. Continuity constraint in elastic optical network.

Regarding the contiguity constraint in EON, it ensures that all frequency slots assigned to a single connection are contiguous, meaning they must be adjacent and form a continuous block within the spectrum. This constraint arises from the way optical signals are transmitted. To efficiently utilize the flexible spectrum provided by EON, a connection must use contiguous slots to avoid signal dispersion and maintain coherent transmission across the network. The frequency slots allocated to a connection cannot be scattered across the spectrum; they must form a single, continuous block. By maintaining contiguity, the available spectrum is

utilized more effectively, reducing fragmentation and improving overall network capacity. Optical equipment, such as transponders and filters, typically operates over contiguous frequency ranges, making this constraint essential for proper functioning.

Given the high data rates required in flexible optical networks (e.g., 400 Gb/s or 1 Tb/s), one can evaluate the number of required frequency slots of a connection [16] as shown in Equation (1).

$$m = \left\lceil \frac{C}{M \times F} \right\rceil \quad (1)$$

where:

- F is the bandwidth of a frequency slice (12.5 GHz or 6.25 GHz);
- M represents the modulation efficiency in Gb/s/GHz, with possible values of 1, 2, 3, or 4, corresponding to the modulation formats BPSK, QPSK, 8-QAM, and 16-QAM, respectively;
- C is the connection data rate in Gb/s.

Respecting the constraints of continuity, contiguity, and the varying bandwidth requirements of connections is essential for optimal resource management. However, when existing connections are disconnected, the frequency slots they occupy become available, but their arrangement may result in fragmented free zones within the spectrum. Moreover, inefficient routing and allocation strategies can exacerbate this fragmentation. Such fragmentation renders some resources unusable, even when free frequency slots are present, as they cannot be combined to meet new demands. Therefore, it is crucial to monitor and manage this phenomenon to minimize the connection blocking rate and optimize the utilization of available resources

3.2. Proposed Algorithm

This section introduces a proposed algorithm for routing and frequency slot allocation tailored to incoming connections. The method integrates two components: Algorithm 1 and Algorithm 2. Algorithm 2 is embedded within Algorithm 1 to reorganize spectrum resources when the network status, evaluated through spectrum utilization, blocking probability, and fragmentation level exceeds a predefined threshold. The approach centers on monitoring the network's status to trigger rerouting and defragmentation (as described in Algorithm 2) when necessary, prior to establishing a new connection. By adapting routing and spectrum allocation to real-time network conditions, this method ensures both efficiency and uninterrupted service continuity.

The proposed approach takes the following inputs:

- network $G(N, L)$: graph with N nodes and L links;
- connection request $r(s, d, B)$: connection request (source, destination, bandwidth B);
- spectrum state S : current frequency slot allocation;
- k : number of paths to explore.

The output consists of the connection status (success or failure) and the updated spectrum state. Algorithm 1, the primary algorithm, is structured into five steps.

The step 1 consists of computing the k-shortest paths between the source node (s) and the destination node (d) in the graph G using Yen's shortest path algorithm [17] for the incoming connection. This step is followed by the initialization step (Step 2), in which the best path and best block of frequency slots are initialized to null. The threshold from which the rerouting and defragmentation process must be triggered is also defined. Based on the current network conditions at the time a connection needs to be established, a network status is evaluated. This network status adapts to real-time network conditions, ensuring more efficient resource utilization. It also helps anticipate and address issues such as high fragmentation. Additionally, it allows network operators to fine-tune scaling factors and weights according to specific policies and objectives.

This network status is typically computed using key metrics that represent the state of the network which include spectrum utilization, blocking probability and fragmentation level. Spectrum utilization represents the ratio of occupied frequency slots to the total available slots. Formula (2) shows how to compute it.

$$S_u = \frac{\text{Used Slots}}{\text{Total Slots}} \quad (2)$$

where:

- S_u stands for spectrum utilization;
- UsedSlots: number of currently assigned slots;
- TotalSlots: total number of slots in the spectrum.

Spectrum utilization in EONs measures how efficiently the available frequency spectrum is utilized. It offers valuable insights into network performance, resource availability, and potential points of congestion. If this value is low, it means that the available resources are sufficient, making any intervention unnecessary. On the other hand, a high value may indicate network saturation or increased fragmentation, which limits the efficiency of resource utilization. In such a situation, a reorganization of spectral allocation may be required based on a predefined threshold [18]. The next metric, Blocking Probability (BP), measures the likelihood that a connection request is rejected due to inadequate network resources. It reflects the network's ability to handle traffic demands and is particularly critical in resource-constrained systems. It is calculated using Formula (3).

$$\text{BP} = \frac{\text{Number of Blocked Requests}}{\text{Total Number of Connection Requests}} \quad (3)$$

A high blocking rate indicates that the network is saturated: either connection requests cannot be fulfilled due to a lack of available spectral resources, or the global resources, although present, are too fragmented to accommodate new connections.

The next metric is fragmentation level. Several metrics can be used to evaluate it, including external fragmentation, which is comparable to the one used for

storage memory. External fragmentation is calculated as the ratio between the number of frequency slots contained in the largest fragment of free slots and the total number of free frequency slots. Although this metric is simple to calculate, it does not account for the emergence of numerous small fragments in the optical spectrum as long as the size of the largest block remains unchanged. This is why, in this work, we favor another metric based on Shannon Entropy (SE). In information theory, entropy is used to estimate the amount of information contained in a message. Inspired by this concept, the SE metric was defined to quantify the fragmentation of the optical spectrum [19]. To calculate the SE metric, it is assumed that the optical spectrum is divided into S total frequency slots and contains η free fragments. Each fragment i ($1 \leq i \leq \eta$) contains S_i frequency slots. Formula (4) is used to express the fragmentation of the optical spectrum.

$$SE = \sum_{i=1}^{\eta} \frac{S_i}{S} \ln \left(\frac{S}{S_i} \right) \quad (4)$$

The advantage of this metric is that it accounts for the presence of large blocks of contiguous frequency slots. This metric decreases as the fragments of blocks become larger. Its value does not depend solely on the largest fragment but considers all fragments. The SE metric increases with fragmentation; the more fragmented the spectrum, the higher the SE metric value. Based on the previous metric, we define network status metric as their combination (Formula (5)).

$$\text{Network}_{\text{Status}} = \alpha \cdot S_u + \beta \cdot \text{BP} + \gamma \cdot \text{SE} \quad (5)$$

where α, β, γ are respectively weights for spectrum utilization, blocking probability and fragmentation level. This metric combines multiple criteria to prevent unnecessary triggering of defragmentation or rerouting. It enables dynamic reorganization tailored to the current state of the network.

At step 3, Algorithm 1 iterates through all candidate paths (P), which were pre-computed using Yen's k-shortest path. For each path, it identifies all contiguous ranges of free slots that could accommodate the connection request. The Best-Fit strategy is then applied to select the smallest block of contiguous free slots that satisfies the required number of slots. If no suitable block is found, the algorithm skips further evaluation of that path and proceeds to the next one.

If a valid block is identified, the algorithm computes the new network status considering the use of the identified block with formula 5. This status is then compared to the predefined threshold. If it falls within acceptable limits, the current path and block are considered the best option. The algorithm updates the BestPath and BestBlock variables with the selected path and block as they meet the requirements. The loop terminates early, as a suitable allocation has been found, eliminating the need to evaluate the remaining paths.

The fourth step of Algorithm 1 is the final decision-making stage of the Routing and Spectrum Allocation (RSA) algorithm. It determines whether a connection request can be successfully accommodated and handles cases where rerouting or reorganization is required. If a valid path (BestPath) and a suitable block of

frequency slots (BestBlock) have already been identified, the algorithm allocates these slots to the connection request and updates the spectrum state S to reflect the new allocation.

However, if no valid allocation is found (BestPath is NULL), Algorithm 1 execute it step five. It consists of executing Algorithm 2 to perform rerouting followed by defragmentation. The first step of Algorithm 2 performs rerouting with the strategie make before break. The primary objective of this step is to optimize spectral resources by rerouting currents connections to more efficient paths. This redistribution of traffic balances the load, improves overall performance, and enhances the network's capacity to accommodate future demands. Connections are prioritized based on bandwidth requirements, with lower-bandwidth connections addressed first to minimize disruptions. This prioritization simplifies the rerouting process and ensures effective traffic redistribution. Using Yen's k-shortest path algorithm, alternative paths are generated and evaluated to verify they meet the necessary bandwidth requirements. To ensure seamless rerouting and service continuity, a make-before-break strategy [20] is employed. This approach establishes a new path for the connection before disconnecting the existing one, thereby preventing service interruptions during the transition. If a suitable path is identified, the connection is seamlessly rerouted to this new path. If no viable path is available, the connection remains on its current route to maintain uninterrupted service.

The rerouting process is followed by step 2 of Algorithm 2 which performs defragmentation. It begins by analyzing the spectral resources to identify fragmented segments, small, scattered blocks too small to meet bandwidth requirements. Each active connection ($c \in C$) is evaluated to determine if it can be moved to a more optimal spectrum block. Reallocating connections consolidates fragmented segments into larger continuous blocks, maximizing efficiency. For each connection, the largest contiguous free spectrum block is identified and allocated using the Best-Fit allocation strategy, which matches the block closely to the connection's bandwidth requirement, minimizing resource waste. For instance, if a connection needs 20 GHz and available blocks are {30 GHz, 50 GHz, 25 GHz}, the 25 GHz block is chosen. After reallocation, the previous spectrum block is released for reuse, ensuring no conflicts and optimizing resource utilization. This iterative process repeats for all connections until the spectrum is fully reorganized, enhancing the network's performance and its ability to handle future demands.

After executing Algorithm 2, the process returns to Algorithm 1 (from line 20 to 25) to attempt finding a path and spectrum block for the incoming connection. With the network's updated state following the execution of Algorithm 2, the likelihood of discovering an available path and frequency slots is significantly increased.

For practical purposes, Algorithm 1, the primary algorithm that integrates Algorithm 2 to perform rerouting and spectrum resource defragmentation when

needed, will be referred to as Dynamic Threshold-Based Routing and Spectrum Allocation with Fragmentation Awareness (DT-RSAF). Dynamic Threshold-based (DT) indicates the algorithm's use of a threshold mechanism to dynamically adapt to network conditions. Routing and Spectrum Allocation (RSA) highlights its primary function of efficiently routing and allocating spectral resources. Fragmentation Awareness (F) emphasizes its capability to account for and address spectrum fragmentation within the network.

Algorithm 1: DT-RSAF

```
1  Step 1: Find the k-shortest paths
2  Paths = YenKShortestPaths (G, s, d, k)
3  Step 2: Initialization
4  BestPath = NULL, BestBlock = NULL, Set Threshold
5  Step 3: Evaluate each path to find the best allocation
6  For each path P in Paths:
7      Compute RequiredSlots = ceil(B/F)
8      Identify AvailableBlocks = FindContiguousFreeSlots (P, S)
9      Find the block using Block = BestFit (AvailableBlocks, RequiredSlots)
10     If Block is not NULL:
11         Netowrk_Status = EvaluateStatus (S, P, Block, RequiredSlots) (formula 5)
12         If Netowrk_Status < Threshold
13             BestPath = P, BestBlock = Block, Break
14 Step 4: Check if allocation is possible
15 If BestPath is not NULL:
16     AllocateSlots (S, BestPath, BestBlock, RequiredSlots)
17     Return Success
18 Step 5: If necessary perform rerouting and defragmentation
19 Else
20     Algorithm 2
21     For each path P in Paths:
22         Identify AvailableBlocks = FindContiguousFreeSlots (P, S)
23         Find the block using Block = BestFit (AvailableBlocks, RequiredSlots)
24         If Block is not NULL: BestPath = P, BestBlock = Block, Break
25     If BestPath is not NULL: AllocateSlots (S, BestPath, BestBlock, RequiredSlots), return success
26 Else return Failure
```

Algorithm 2: Rerouting Followed by Defragmentation

Input:

- 1 $C \leftarrow$ Set of active connections in the network
- $S \leftarrow$ Spectral resource state of the network
- $R \leftarrow$ Set of routing paths available for each connection

Output:

- 2 $S' \leftarrow$ Optimized spectrum allocation
- $R' \leftarrow$ Updated routing paths for connections

Step 1: Rerouting (Move before break)

- 3 Sort connections in C based on priority (less bandwidth)
- 4 For each connection $c \in C$:
 - 5 Find alternate paths in R (use Yen's K-Shortest Path)
 - 6 If an alternate path match with bandwidth requirement
 - 7 Reroute connection c to the new path
 - 8 Else Keep the original route
 - 9 End If
- 10 End For

Step 2: Defragmenting (Move before break)

- 11 Identify fragmented segments in S
- 12 For each connection $c \in C$
 - 13 Find the largest continuous free spectrum block in S
 - 14 Reallocate c to the new block using a best-fit allocation strategy
 - 15 Remove c from the previous occupied spectrum
- 16 End For

3.3. Experimentation Set Up

Several experiments were conducted in this section. The first one focusing on evaluating execution times and analyzing the efficiency of the proposed algorithm in solving the Routing and Spectrum Allocation (RSA) problem within a reasonable timeframe. For this purpose, a network topology consisting of six nodes, as illustrated in **Figure 3**, was used.

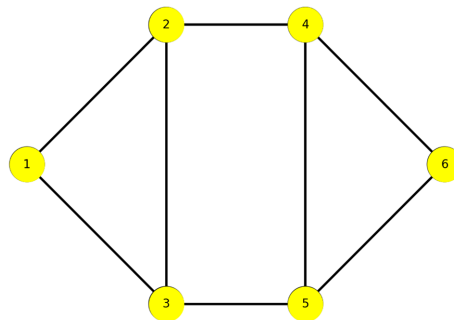


Figure 3. Small network of six nodes.

On this network topology (**Figure 3**), 20 connections were generated with bandwidths expressed in frequency slots and uniformly distributed across the set $S = \{10, 15, 20, 25\}$ and the average executing time of each approach was recorded.

Other experiments were also conducted to evaluate the performance of each approach of solving RSA problem by using blocking probability and the Bandwidth Fragmentation Ratio (BFR).

Blocking probability is a key performance metric in Elastic Optical Networks (EONs) that measures the likelihood of a connection request being denied due to insufficient available resource. The Bandwidth Fragmentation Ratio (BFR) is a metric used in Elastic Optical Networks (EONs) to quantify the degree of fragmentation in the spectrum resources.

$$\text{BFR} = \frac{\text{Number of Fragmented spectrum slots}}{\text{Total Spectrum slots available}} \quad (6)$$

For this end, two networks topologies: NSFNET (14 nodes, 22 links) [21], COST 239 (11 nodes, 26 links) [22] were used. For dynamic traffic, the frequency slot requests for each connection were modelled as a Poisson process. **Table 1** shows a simulation network parameter.

Table 1. Network simulation parameters.

Bandwidth of each frequency slot	12.5 GHz
Overall bandwidth	4000 GHZ
Number of frequency slots per link	320 FSs
Data transmission rates	10, 50, 100, 400 Gbs

Given the relative importance of spectrum utilization, blocking probability and fragmentation level, the components of the network status evaluation, following weights were used: $\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.3$ to compute it (formula 5). The threshold value was empirically determined to be 70%, indicating that the proposed approach will trigger rerouting followed by defragmentation when the network status surpasses this level. The performance of DT-RSAF is evaluated against the heuristic LBFA proposed in [8], the metaheuristic IWO-RSA presented in [15], and the simpler K-Shortest Path Routing and Spectrum Allocation (KSP-RSA) method.

This experiment was implemented in Python 3.13 on a system featuring a Core i7 processor and 16 GB of RAM, enabling the collection of average execution times for comparative analysis and other metrics like blocking probability and bandwidth fragmentation ratio.

4. Results and Discussions

4.1. Results

Table 2 displays the average execution time of each method obtained by using network topology of **Figure 4**. The K-Shortest Path Routing and Spectrum

Assignment (KSP-RSA) algorithm is a simplified version of the Dynamic Traffic Routing and Spectrum Assignment with Fragmentation-awareness (DT-RSAF) algorithm, operating without rerouting and defragmentation functionalities.

Table 2. Average execution time of different RSA Approach.

RSA resolution approach	Average execution time (ms)
LBFA [10]	6000
IWO-RSA [15]	7800
Integer Linear Programming (ILP) [6]	5,400,000
KSP-RSA	3000
DT-RSAF	6020

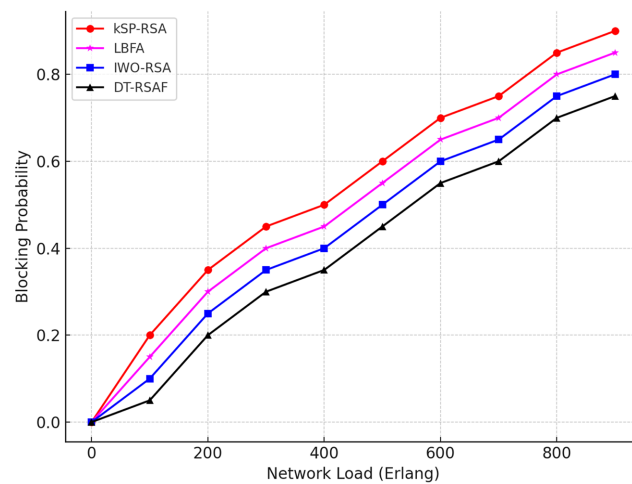


Figure 4. Connections requests blocking probability on NSFNET topology.

Among the listed approaches, KSP-RSA has the shortest average execution time at 3000 ms. In contrast, Integer Linear Programming (ILP) has a significantly longer execution time of 5,400,000 ms. The execution times for LBFA and DT-RSAF are nearly identical, slightly shorter than that of IWO-RSA, yet longer than KSP-RSA. However, when compared to ILP, both DT-RSAF and LBFA are markedly more efficient in terms of computation time.

Figure 4 illustrates by using NSFNET topology the relationship between traffic load, measured in Erlangs, and the blocking probability for four different Routing and Spectrum Allocation strategies: KSP-RSA (red curve), LBFA (green curve), IWO-RSA (magenta curve) and DT-RSAF (black curve).

As the traffic load increases from 0 Erlangs to 800 Erlangs, the blocking probability rises for all four strategies, indicating higher network congestion and resource contention at higher traffic. The figure emphasizes that DT-RSAF outperforms KSP-RSA LBFA and IWO-RSA by achieving lower blocking probabilities, particularly under heavy traffic conditions. This indicates that DT-RSAF is more effective in optimizing resource utilization and reducing connection failures.

Figure 5 offers by using COST 239 topology a comparison similar to the previous one, showcasing the blocking probability of the KSP-RSA, LBFA, IWO-RSA and DT-RSAF strategies as a function of traffic load.

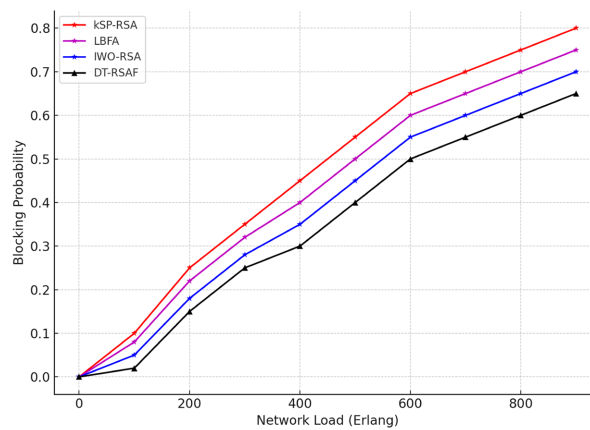


Figure 5. Connections requests blocking probability on COST 239 topology.

In this case, the increase in blocking probability is slightly less pronounced reaching around 80 % for KSP-RSA when the load increase beyond 800 erlangs. As observed earlier, the DT-RSAF strategy consistently delivers the best performance by achieving the lowest blocking probability among all the four strategies.

Figure 6, using the NSFNET topology, illustrates the Bandwidth Fragmentation Ratio (BFR) for the KSP-RSA, LBFA, IWO-RSA and DT-RSAF strategies as a function of network load. DT-RSAF consistently demonstrates the lowest bandwidth fragmentation. At a load of 900 erlangs, KSP-RSA exhibits a BFR between 77% and 80%. LBFA offers slightly better performance, with a BFR ranging from 75% to 77%. IWO-RSA surpasses these two approaches, displaying a BFR of approximately 76%, indicating a modest reduction in fragmentation. Finally, DT-RSAF stands out with the best overall performance, achieving a BFR between 74% and 75%, demonstrating increased efficiency in reducing fragmentation and resource blocking.

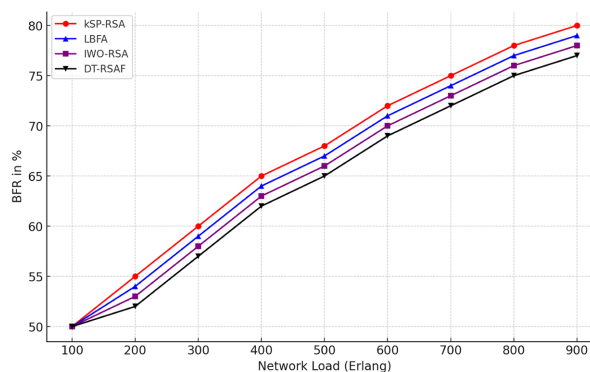


Figure 6. Bandwidth Fragmentation Ratio (BFR) of NSFNET topology.

Figure 7 presents the Bandwidth Fragmentation Ratio (BFR) for KSP-RSA, LBFA, IWO-RSA and DT-RSAF strategies using the COST 239 topology. It reinforces that DT-RSAF consistently achieves lower fragmentation, as also observed in **Figure 6** with the NSFNET topology.

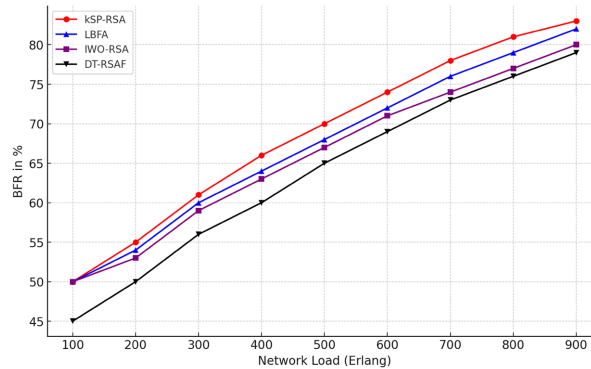


Figure 7. Bandwidth Fragmentation Ratio (BFR) of COST 239 topology.

4.2. Discussions

The results in **Table 2** show that with an average execution time of 3000 ms, the K-Shortest Path Routing and Spectrum Allocation (KSP-RSA) algorithm stands out as the most efficient approach in terms of computational time. Its speed is primarily due to its simplicity, as it avoids rerouting and defragmentation processes, which reduces computational overhead. The Load Balancing First Algorithm (LBFA) and DT-RSAF have similar execution times, approximately 6,000 ms. Both algorithms incorporate more sophisticated strategies, such as load balancing and fragmentation awareness, which increase their computational demands compared to KSP-RSA. The Invasive Weed Optimization-based RSA (IWO-RSA) algorithm, with an execution time of 7800 ms, employs optimization techniques to enhance routing and spectrum allocation decisions. While this approach improves performance, it also adds computational complexity, leading to longer execution times. Lastly, the Integer Linear Programming (ILP) method, though capable of producing optimal solutions, has a significantly higher execution time of 5,400,000 ms. Its intensive computational requirements make it impractical for real-time applications in dynamic network environments. The results presented in **Figures 4-7** highlight the advantages of DT-RSAF in optimizing the utilization of frequency slots and reducing the blocking probability in EONs.

Figure 4 and **Figure 5**, which analyze blocking probability using the NSFNET and COST 239 topologies, respectively, demonstrate the superior performance of the DT-RSAF strategy compared to KSP-RSA, LBFA and Iwo-RSA. The blocking probability for DT-RSAF remains consistently lower, even under heavy traffic conditions. This indicates that DT-RSAF effectively utilizes network resources to accommodate connection requests. By incorporating network status monitoring that adapt to real-time network conditions, DT-RSAF can balance resource

allocation efficiency. This capability minimizes the likelihood of connection failures, even when network load approaches saturation, showcasing the significant impact of rerouting and defragmentation. The Load Balancing First Algorithm (LBFA) demonstrates superior performance in terms of blocking probability compared to IWO-RSA, while also exhibiting a more efficient execution time, particularly when contrasted with IWO-RSA. Although Integer Linear Programming (ILP) can yield optimal solutions, its computational demands render it unsuitable for real-time execution scenarios.

Figure 6 and **Figure 7**, which compare the Bandwidth Fragmentation Ratio (BFR) across the three strategies, further emphasize DT-RSAF's efficiency. DT-RSAF consistently achieves the lowest fragmentation ratios significantly outperforming KSP-RSA, LBFA IWO-RSA. The reduced fragmentation under DT-RSAF highlights its ability to maintain larger contiguous frequency blocks, which are essential for accommodating high-bandwidth requests. This performance is further enhanced by rerouting and defragmentation which reorganizes existing connections to free up necessary resources, reducing fragmentation and making the network more adaptable to dynamic traffic demands.

The network status monitoring of metric such spectrum utilization, fragmentation level and blocking probability and performing a spectrum reorganization when it reaches a threshold by rerouting and defragmentation some existing connections brings advantages to DT-RSAF and make it more efficient by handling efficient blocking probability and bandwidth fragmentation with reasonable execution time.

5. Conclusions

This study tackles the challenges of routing and spectrum allocation in Elastic Optical Networks (EONs). By developing and evaluating the DT-RSAF algorithm, which combines network status monitoring with the reorganization of existing connections when a threshold is exceeded, it demonstrates notable enhancements in network performance, particularly in reducing blocking probability, bandwidth fragmentation, and execution time. DT-RSAF reduces blocking probability by 15% under heavy traffic. At a load of 900 Erlangs, DT-RSAF achieved the lowest BFR (74% - 75%) compared to IWO-RSA (76%), LBFA (75% - 77%), and KSP-RSA (77% - 80%). On a small network, DT-RSAF had an average execution time of 6020 ms, similar to LBFA (6000 ms) but slower than KSP-RSA (3000 ms). IWO-RSA required 7800 ms, while ILP was impractical for dynamic environments, taking 5,400,000 ms. These results confirm DT-RSAF's efficiency in resource allocation, network performance optimization, and maintaining reasonable execution times under varying conditions.

The results highlight that DT-RSAF consistently outperforms approaches like KSP-RSA, LBFA and IWO-RSA in both blocking probability and bandwidth fragmentation ratio (BFR), as evidenced by simulations on NSFNET and COST 239 topologies. By dynamically adapting to real-time network conditions, the proposed

algorithm ensures efficient allocation of frequency slots, minimizes resource fragmentation, and significantly reduces connection failures under high traffic loads.

The network status monitoring, combined with a rerouting and defragmentation process when necessary, allows DT-RSAF to effectively address the challenge of routing and spectrum allocation with minimum blocking connection even under high traffic load and reasonable execution time. The difficulty of this work lies in determining an optimal threshold and network status monitoring parameters. Future work will explore machine learning techniques to identify optimal values.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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