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Spectrum Defragmentation Window in SDM-EON Networks

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Abstract Space division multiplexing (SDM) technology expands the capacity of elastic optical networks (EONs) by adding spatial dimensions, positioning SDM-EONs as a strong candidate for future high-throughput infrastructures. However, SDM introduces new challenges, especially vertical fragmentation, where frequency slots become misaligned across multiple cores. This fragmentation decreases spectral efficiency, reduces resource availability, and increases connection blocking. This work proposes WDefrag, a novel RMSCA algorithm that tackles these issues through Slot Window Defragmentation, an original strategy developed in this study. WDefrag segments the spectrum into cost-evaluated windows and identifies regions where fragmentation most severely limits allocation. The algorithm reallocates resources locally, avoids unnecessary disruptions, and improves spectrum organization while managing crosstalk and fragmentation in both spatial and spectral dimensions. WDefrag operates in both proactive and reactive modes and adjusts window sizes to match traffic dynamics. Simulations compare it against non-defragmenting and state-of-the-art approaches. WDefrag outperforms these baselines by up to 30% in bandwidth blocking reduction, particularly in proactive scenarios. By applying cost-aware decisions and prioritizing fragmented regions that limit connectivity, WDefrag enhances spectrum utilization and delivers consistent performance improvements under real network demands.

Keywords: Defragmentation, SDM-EON Network, Spectrum Fragmentation

1 Introduction

The rise of data-intensive applications, such as Industry 4.0, the Internet of Things (IoT), and fifth-generation mobile telecommunications (5G), has fueled an unprecedented demand for optical networks. To satisfy this demand, it is crucial to leverage various multiplexing technologies that enhance the utilization of optical fibers and lightpaths. Consequently, these networks now employ advanced multiplexing techniques to maximize efficiency and performance IEEE Standards Association [2023]. While Elastic Optical Networks (EONs) provide significant spectral efficiency by flexibly adapting to varying bandwidth requirements on lightpaths, they are approaching the physical limitations of current optical fibers in the frequency domain—a phenomenon known as the capacity scarcity problem. To tackle this, Spatial Division Multiplexing (SDM) has emerged as a promising solution within EONs. By facilitating the parallel use of multiple transmission cores within a single optical path, SDM-EONs significantly boost transmission capacity, offering up to 30% more capacity than conventional optical fibers Sharma *et al*. [2022].

The adoption of SDM, however, transforms the classic Routing and Spectrum Allocation (RSA) problem into the more complex Routing, Modulation, Spectrum, and Core Assignment (RMSCA) problem Paira *et al*. [2021]. RMSCA introduces new dimensions to the resource allocation challenge, as it must now account for core selection and modulation format in addition to the usual spectrum and routing decisions. The RMSCA problem imposes strict physical-layer constraints, particularly continuity and contiguity. The continuity constraint requires that the same set of spectrum slots be preserved across all links in the lightpath, while the contiguity constraint demands that the slots form an uninterrupted frequency block. These constraints, already limiting in EONs, become more complex in SDM-EONs due to the added requirement of minimizing inter-core crosstalk. This combination increases the difficulty of finding feasible lightpaths and leads to spectrum fragmentation and inefficient resource usage. This transition necessitates identifying the optimal spectrum alongside the ideal core allocation to effectively mitigate crosstalk and fragmentation while satisfying continuity and contiguity constraints.

While SDM-EON technology offers substantial advantages in enhancing transmission capacity, its deployment also introduces new complexities, particularly exacerbating spectrum fragmentation. This issue, already present in traditional EONs, becomes even more intricate in SDM-EONs due to the spatial dimension introduced by multiple transmission cores, which also leads to vertical fragmentation. Generally, spectrum fragmentation arises when network resources (frequency slots) become scattered and underutilized, primarily due to the dynamic allocation and deallocation of lightpaths with varying bandwidth needs. These scattered gaps in the spectrum are often too small to accommodate new lightpaths, resulting in inefficient resource utilization. As lightpaths are continuously added and removed, the degree of fragmentation intensifies, diminishing overall spectrum efficiency and elevating the risk of network congestion. Consequently, high fragmentation increases the probability of service blockages, impacting the network's ability to support growing traffic demands.

Beyond spectrum fragmentation, SDM-EON networks face another challenge: fragmentation between the cores of multi-core optical fibers, also termed vertical fragmentation. This problem stems from the fact that SDM fibers contain multiple cores, enabling parallel transmission of lightpaths. However, complications arise when crosstalk—interference between signals in adjacent cores—further compounds the issue. Crosstalk manifests when a portion of the signal from one core 'leaks' into a neighboring core, causing unwanted interference. This phenomenon is particularly problematic in SDM-EON networks, where multiple cores are employed simultaneously to enhance transmission capacity. Crosstalk degrades signal quality, increases transmission errors, and complicates spectrum allocation. To mitigate these effects, network operators must consider crosstalk during spectrum allocation, implementing strategies to minimize its impact and ensure reliable performance. Yet, these mitigation efforts can inadvertently lead to increased vertical fragmentation.

This paper proposes WDefrag, a novel RMSCA algorithm designed to reallocate the spectrum, managing both horizontal and vertical fragmentation, as well as crosstalk, in SDM-EON technology. The approach prioritizes defragmentation through spectrum reallocation along the same route, eliminating the need for rerouting. This decision is motivated by practical and operational factors, as spectrum reallocation typically results in lower downtime and avoids the complexities and delays associated with establishing new connections along alternative routes. A key feature of WDefrag is the introduction of the Slot Window Defragmentation technique. This method dynamically defines localized windows along critical routes, concentrating defragmentation efforts on areas where fragmentation most affects resource availability. By reorganizing spectrum slots within these windows, WDefrag reduces computational overhead while efficiently addressing both horizontal and vertical fragmentation. Unlike conventional defragmentation strategies that attempt to reorganize the entire network spectrum, WDefrag confines reallocating efforts to localized windows, which minimizes network-wide disruption and enhances performance.

Additionally, WDefrag leverages a cost-based equation to prioritize reallocation decisions, ensuring optimal resource usage with minimal disruption. This cost function is tailored to evaluate which slot windows are most suitable for reallocation by considering demand patterns and aiming to free larger contiguous regions of spectrum with minimal computational effort. This combination distinguishes WDefrag from conventional defragmentation strategies that attempt to reorganize the entire spectrum without first segmenting it into localized windows. Unlike prior approaches, WDefrag dynamically identifies and prioritizes slot windows where defragmentation will yield the greatest resource gains with minimal computational cost, enabling a more adaptive and scalable solution. To the best of our knowledge, this is the first approach to introduce a window-based defragmentation strategy specifically designed to localize spectrum reallocation within SDM-EONs. The Slot Window Defragmentation technique organizes spectrum resources into dynamically sized, cost-evaluated windows, enabling precise reallocation where fragmentation most limits resource availability. This segmentation allows WDefrag to reduce blocking while preserving spectral continuity and mitigating crosstalk. By acting simultaneously on vertical and horizontal fragmentation, it meets SDM-EON challenges with an efficient, traffic-aware defragmentation process that avoids the overhead of global reallocation or greedy heuristics.

Our proposed solution reduces the likelihood of worsening crosstalk by allocating the spectrum more effectively along existing paths. By focusing on spectrum reallocation, network operators can maximize bandwidth utilization and improve infrastructure efficiency, particularly during periods of high network traffic. Rerouting, in contrast, may introduce delays and additional congestion. Therefore, prioritizing spectrum reallocation allows networks to maintain performance levels, reduce the risk of service disruptions, and enhance overall network efficiency.

The remainder of this paper is structured as follows: Section 2 reviews the concepts and related work concerning defragmentation in SDM-EONs. Section 3 elaborates on the defragmentation techniques employed in our algorithm. Section 4 presents the simulation results and their analysis, and Section 5 concludes the paper with final remarks.

2 Concepts and Related Work

In SDM-EON networks, fragmentation occurs in two primary forms: horizontal and vertical. Figure 1 illustrates the differences between horizontal and vertical fragmentation, as well as how crosstalk affects spectrum allocation. Horizontal fragmentation happens when free spectrum slots are scattered across a link or core, making it difficult to find contiguous blocks of available slots for a connection. Vertical fragmentation, on the other hand, occurs when free slots are available on different cores of the same link but are not aligned with free slots on the corresponding cores of other links along the path within a free area crosstalk. Crosstalk exacerbates both types of fragmentation because network operators must avoid or minimize crosstalk when allocating spectrum. Crosstalk occurs when two lightpaths share the same spectral index in adjacent cores, resulting in signal interference that compromises signal quality and increases transmission errors. This interference arises because lightpaths occupying the same frequency index in neighboring cores risk signal overlap, which confuses transponders and distorts the multiplexed signals.

Although optical systems can tolerate crosstalk within acceptable limits, exceeding these thresholds significantly degrades transmission quality. To mitigate this risk, spectrum allocation strategies implement techniques that ensure lightpaths with the same spectral index are assigned to non-adjacent cores within the same link. While this method effectively reduces interference, it imposes constraints that disrupt spectrum continuity between cores, often causing scattered and underutilized frequency slots—a condition known as vertical fragmentation. Although vertical fragmentation poses a challenge, this tradeoff is often necessary to maintain signal integrity and ensure reliable data transmission. To mit-

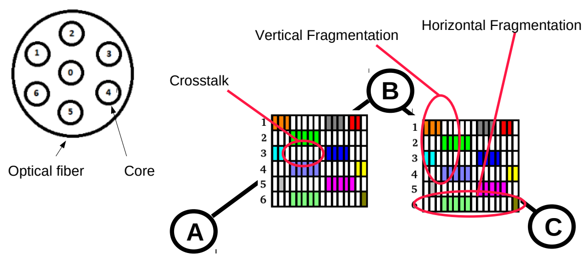

Figure 1. EON-SDM Fragmentation and inter-core Crosstalk

igate this, operators often leave certain slots unused or avoid spectrum areas with high crosstalk, even if those slots are technically available. This strategy, however, increases fragmentation, making it more difficult to find contiguous free spectrum blocks for new connections and reducing overall network performance and resource utilization.

Figure 1 clearly illustrates how crosstalk mitigation leads to vertical fragmentation. In particular, cores 1 to 4 show that identical spectral indices are intentionally not used across adjacent cores to avoid crosstalk. Although this constraint reduces interference, it prevents the alignment of available slots across cores, resulting in underutilized spectrum. For example, even when some slots appear free in one core, they cannot be used in adjacent ones due to crosstalk constraints, which breaks the spectrum continuity and produces vertical fragmentation. This visual example reinforces how efforts to mitigate crosstalk directly contribute to increased fragmentation in the vertical dimension.

Addressing horizontal and vertical fragmentation is challenging; the literature extensively discusses strategies aimed at minimizing fragmentation caused by crosstalk in SDM-EON networks. Various defragmentation solutions have been proposed to optimize contiguous free spaces and reduce fragmentation, ranging from proactive to reactive techniques, with or without service interruption and the use of additional equipment. In SDM-EON networks, defragmentation is accomplished by reallocating the optical path within the same or a different spectrum band Sharma *et al.* [2022]. Techniques such as SS-DC (Same Spectrum – Different Core) and DS-SC (Different Spectrum – Same Core), along with additional defragmentation methods, play a crucial role in improving overall network performance.

Horizontal fragmentation remains a persistent problem in each core of SDM-EON networks and is now further complicated by spatial crosstalk. Fragmented spectral slots, when unevenly distributed across cores, limit viable allocations due to interference constraints—thus increasing vertical fragmentation. Even when slots appear available in adjacent cores, they may become unusable if lightpaths share the same spectral index and risk exceeding acceptable crosstalk thresholds. Therefore, fragmentation in one dimension directly influences fragmentation in the other, amplifying resource inefficiency.

The study by Zhao *et al.* [2018] highlights the main challenges in SDM-EON networks, particularly focusing on strategies to minimize fragmentation and mitigate the impact of crosstalk. In SDM-EON networks, each core operates with its own set of spectrum slots, and crosstalk arises when neighboring cores have lightpaths occupying spectrum bands with the same slot indices. This interference between cores complicates the spectrum allocation process, making it essential to carefully manage both core and spectrum resources to reduce crosstalk and improve network performance.

SS-DC and DS-SC stand out as key approaches for managing crosstalk and fragmentation. SS-DC involves relocating the optical path to a different core on the same link while maintaining the same spectrum slots. The main challenge with SS-DC arises when the network is congested, making it difficult to find available slots on different cores. Nevertheless, DS-SC reallocates the optical path to a different spectrum on the same core when no spectrum resources are available on other cores. However, DS-SC may cause service interruptions due to the need to reconfigure the source and destination transponders. These two defragmentation techniques are further highlighted in Section 3, in Figures 3 and 4.

Complementary to defragmentation strategies, the literature addresses two primary approaches for managing crosstalk: XT-avoid Chatterjee *et al.* [2021] Zhang *et al.* [2022] and XT-estimated Sharma *et al.* [2022] Zhao *et al.* [2018] Brasileiro *et al.* [2020]. XT-avoid prevents the allocation of lightpaths in slots with identical indices in neighboring cores, while XT-estimated calculates the level of crosstalk to assess the maximum acceptable interference under similar conditions.

The authors in Ahmed *et al.* [2022] highlight the main differences between the XT-estimated and XT-avoid approaches, which lie in their resource allocation strategies and utilization. The XT-estimated approach allows resource allocation in neighboring modes and cores as long as the induced crosstalk remains within a predefined limit, resulting in better resource utilization but requiring more computation time and being more complex to manage. In contrast, the XT-avoid approach prohibits allocation in neighboring modes and cores, which can lead to higher blocking rates and lower resource utilization. However, this approach simplifies management and requires less computation time.

The analysis shown in Chatterjee *et al.* [2021] highlights XT-avoid's simplicity and ease of management, in contrast to the complexity and increased computational demands of XT-estimated. XT-avoid allows for precise control of crosstalk-affected slots, whereas XT-estimated struggles with consistent identification, complicating management efforts. XT-avoid does not require calculating volatile crosstalk values, streamlining the problem model and enhancing efficiency Zhang *et al.* [2022]. However, XT-avoid can lead to lower resource utilization compared to XT-estimated. Although the principle of XT-avoid is more economical in terms of management, our results demonstrate that when combined with an efficient cost function, XT-avoid can yield significantly better blocking rate results than XT-estimated. XT-avoid enables a consistent reallocation pattern, while XT-estimated adopts a more greedy approach that exploits crosstalk.

Expanding on the challenges posed by XT-estimated, Sharma et al. Sharma *et al.* [2022] emphasize the importance of mitigating fragmentation while keeping XT-estimated impairments within acceptable thresholds. Their study highlights the critical need for maintaining spectrum contiguity and continuity for each established optical path in EON networks. Additionally, they point out how crosstalk increases the computational complexity of RMSA (Routing, Modulation, and Spectrum Assignment) algorithms in EON networks. Zhao et al. Zhao *et al*. [2018] introduced an RMSCA algorithm for spectrum defragmentation based on spectrum compression with XT-estimated, allowing the exploitation of crosstalk to free up additional resources.

The study by Brasileiro et al. Brasileiro *et al*. [2020] proposes a non-impact spectral defragmentation solution that combines push-pull and fast switching techniques to reallocate optical circuits in SDM-EONs without disrupting active traffic. The process begins by identifying free slots on other cores of the same fiber that match the indices of the currently allocated circuit. If the required slots are occupied, the algorithm checks for available slots in other cores on the same link. The main switch employs fast switching for rapid reconfiguration, while the push-pull technique temporarily displaces the circuit's spectrum to create additional space before restoring the original allocation—ensuring uninterrupted service. This method minimizes latency and maintains service continuity, outperforming traditional techniques that require circuit interruptions. The method also leverages XT-estimated and applies an equation to determine exploitable crosstalk limits. However, our results indicate that, depending on the defragmentation management strategy, XT-avoid can still outperform XT-estimated in terms of overall network performance, highlighting the importance of choosing the right approach based on specific network conditions. Our paper adopts the push-pull and fast switching mechanisms to reduce the impact of defragmentation on service interruption during spectrum reallocation.

Expanding on the broader goals of defragmentation, the main objective is to maintain as many contiguous free slot segments as possible, optimizing resource availability Chatterjee *et al*. [2018]. Defragmentation enhances resource allocation efficiency by minimizing blocked connections and delaying network congestion. This process reorganizes the spectrum by grouping optical paths and creating larger free spaces for new demands. The effectiveness of defragmentation also depends on the spectrum allocation policy employed, such as first-fit, last-fit, or others Buffa *et al*. [2020]. Furthermore, defragmentation often requires reconfiguring the optical path to a different spectrum to improve utilization and increase access to service requests Wang *et al*. [2021]. Wang et al. Wang *et al*. [2021] designed an algorithm based on Multiple Criteria Decision Making (MCDM), which aims to optimize spectrum utilization while reducing network blocking rates. MCDM aids decision-making by considering multiple criteria simultaneously, making it a valuable tool for optimizing defragmentation strategies in complex network environments.

In line with optimizing defragmentation, the study in Singh *et al*. [2018] classifies defragmentation approaches into proactive or reactive, involving redirection and reallocation with or without service interruption. In Posam *et al*. [2020], the authors highlight three main approaches to defragmentation: fragmentation-aware, proactive, and reactive. Fragmentation-aware defragmentation uses a fragmentation metric to reallocate resources before new demands arrive, aiming to reduce fragmentation and delay resource congestion. Proactive defragmentation is performed periodically to prevent traffic congestion and extend network overcapacity. This method is implemented in our algorithm and has demonstrated highly relevant results. On the other hand, reactive defragmentation is triggered by specific events, such as fragmentation metrics or blocked requests. It reconfigures some or all existing connections when a new request is blocked. While this method can resolve blocking issues, it is generally less effective as it is only activated when resources are already scarce.

Although defragmentation can interrupt the optical path for reallocation, several physical layer techniques have been designed to minimize or eliminate this issue. These techniques include re-optimization, make-before-break, push-pull, and hop-tuning Wang [2019]. Some studies, such as Zhang *et al*. [2014], have demonstrated the effectiveness of the push-pull technique in performing efficient spectrum defragmentation without requiring additional resources, affecting stability, or causing detrimental effects on traffic distribution. Push-pull relies on dynamic frequency tuning, allowing for the reconfiguration and reallocation of the optical path without requiring extra transponders. Additionally, previous studies have proposed defragmentation methods that operate without operator intervention or with minimal downtime. For instance, Wang and Mukherjee [2013] discusses an automatic defragmentation approach, while Proietti *et al*. [2012] presents a method with minimal unavailability, achieving downtime as low as $400\mu s$.

While defragmentation techniques have significantly reduced blocking rates in traditional EON networks, as demonstrated in several works such as Saad and Luo [2005], Gencata and Mukherjee [2003], Oki *et al*. [2020], and Sawa *et al*. [2019], the application of these methods to SDM-EONs remains underexplored. These efforts, along with the development of new protection techniques and the mitigation of network outages, underscore the critical importance of improving defragmentation strategies. However, despite the advancements in EON defragmentation, there is still a notable gap in research specifically targeting SDM-EON networks. Only a few studies, such as Zhao *et al*. [2018] and Brasileiro *et al*. [2020], have begun to address these unique challenges, indicating the need for further investigation in this area.

Several studies highlight that, even in traditional EONs, defragmentation strategies can be effective in specific scenarios but do not guarantee overall improvement in network-wide fragmentation. For instance, Buffa *et al*. [2020] notes that the effectiveness of specific strategies varies depending on traffic conditions, implying that no single approach consistently delivers network-wide benefits. Similarly, Pathania *et al*. [2017] discusses the limitations of heuristics in reducing fragmentation across different workloads, suggesting that a distributed solution may be necessary for better scalability. Lastly, Wang [2019] emphasizes that these strategies often struggle to maintain spectrum continuity and consistency, which can still result in high blocking rates even after defragmentation.

Measuring fragmentation or spectrum organization is essential for assessing the current state of the network and guiding future allocation and defragmentation decisions. Several studies discuss different fragmentation metrics Wu *et al*. [2014], Buffa *et al*. [2020], Posam *et al*. [2020], Rosa *et al*.

[2012], many of which are originally derived from hard disk analysis. In Wu *et al.* [2014], a metric is proposed to calculate the degree of spectrum continuity, a critical physical constraint in fragmentation analysis. Additionally, Buffa et al. Buffa *et al.* [2020] introduce external fragmentation as their main metric and classify defragmentation approaches as reactive or proactive, with or without service interruption, and with or without redirection. The study in Posam *et al.* [2020] employs the first-fit allocation technique to maintain as many contiguous blocks as possible on one side of the spectrum, reducing further fragmentation. First-fit allocation is the default spectrum allocation policy in optical networks due to its simplicity, which helps keep resources organized and less fragmented.

Defragmentation is classified as an NP-complete problem, especially in optical networks Pathania *et al.* [2017]. This complexity arises from the need to satisfy multiple interdependent constraints—such as spectrum continuity, spectrum contiguity, core assignment, bandwidth requirements, and crosstalk minimization—over all links and cores in the network. As these constraints must be met simultaneously for each candidate lightpath, the search space grows exponentially with the number of connections and available resources, making optimal solutions computationally infeasible in large-scale networks. Additionally, global defragmentation solutions may not always align with local demands, meaning that addressing the entire network does not necessarily reduce blocking rates. These challenges underscore the importance of designing scalable algorithms. Our proposal targets SDM-EON backbones with a small number of high-capacity Tier-1 nodes and long-haul links. In this context, full network reorganization introduces high cost and operational impact without proportional gains. WDefrag avoids this by reallocating spectrum along specific demand routes using localized, cost-evaluated windows.

The Slot Window Defragmentation strategy limits complexity while improving spectral efficiency, ensuring practical deployment in real backbones. This process must account for various factors, including bandwidth requirements, spectrum continuity, spectrum contiguity, and crosstalk. As the number of connections and available resources grows, the exponential increase in possible resource allocation combinations makes finding an optimal solution computationally infeasible. Additionally, global defragmentation solutions may not always align with local demands, meaning that addressing the entire network does not necessarily reduce blocking rates. These challenges underscore the importance of developing new heuristics and algorithms, such as the approach we propose, which focuses on defragmenting demand-specific routes.

Our solution adopts core principles from the literature, such as XT-avoid, SS-DC, and DS-SC, while introducing a window-based strategy to localize and prioritize defragmentation. The Slot Window Defragmentation technique evaluates the best candidate regions for reallocation using a cost-based equation, seeking to maximize spectrum availability with minimal disruption. This mechanism differs from global defragmentation schemes by organizing spectrum in advance and then selecting specific areas for action, rather than reacting across the entire network. While these strategies significantly improve specific network scenarios, it remains crucial to acknowledge that no single method guarantees optimal outcomes across the entire network. The inherent complexity of SDM network dynamics emphasizes the need for continued research into adaptive algorithms capable of addressing these evolving challenges.

Some recent works, such as Dong *et al.* [2024], have proposed Tetris-inspired strategies using a window-based approach for resource reallocation in domains like Compute-In-Memory (CIM). In their context, the term "window" refers to a temporal window for managing reallocation timing. In contrast, WDefrag applies the window concept spatially, defining windows as contiguous frequency slot ranges eligible for reallocation. This spatial windowing enables WDefrag to iteratively scan and optimize spectrum usage, improving defragmentation efficiency across SDM-EONs. Our Slot Window Defragmentation introduces a conceptually distinct approach tailored to the optical networking domain. Specifically designed for SDM-EONs, it dynamically identifies and prioritizes defragmentation regions based on spatial and spectral fragmentation patterns, while addressing challenges unique to this architecture, such as inter-core crosstalk and continuity constraints. Unlike prior techniques, our method formulates defragmentation as a localized, cost-driven windowing process, offering a scalable and adaptive alternative to traditional network-wide reallocation.

In summary, while the literature offers a variety of proactive and reactive defragmentation techniques—ranging from methods that avoid service interruption to those that reallocate resources across different or the same spectrum—the challenge remains in refining the criteria for selecting lightpaths for reallocation. Specifically, further exploration is needed to optimize both vertical and horizontal reallocation strategies, ensuring that these techniques minimize fragmentation and improve overall network efficiency. Vertical fragmentation, particularly relevant in SDM-EON networks, arises from inefficient use of spectrum across multiple cores, while horizontal fragmentation involves the continuity of spectrum allocation within a single core. In response to these challenges, this work proposes an algorithm to reallocate the spectrum of lightpaths, freeing up additional space to accommodate higher traffic demands. This approach simultaneously addresses the issues of crosstalk and spectrum fragmentation, optimizing resource utilization, reducing blocking rates, and enhancing overall network performance.

Our proposed Slot Window Defragmentation introduces a localized and cost-aware spectrum reallocation strategy that addresses the limitations of global defragmentation schemes. By combining window-based segmentation with crosstalk-aware core selection, WDefrag effectively mitigates vertical and horizontal fragmentation in SDM-EONs. Table 1 compares WDefrag with the most relevant defragmentation strategies discussed in the literature.

3 Slot Window Defragmentation

WDefrag introduces the Slot Window Defragmentation technique, a novel and conceptually distinct approach that preprocesses the spectrum by segmenting it into cost-evaluated

Table 1. Comparison of defragmentation strategies in SDM-EON networks.

Reference	Scope	Core Allocation	Defrag. Strategy	Cost-aware	Crosstalk Mitigation	Vertical Frag. Handling	XT Strategy
Zhao *et al.* [2018]	SDM-EON	Fixed Core	Spectrum Compression	No	Partial	No	XT-estimated
Brasileiro *et al.* [2020]	SDM-EON	Dynamic Core	Push-Pull + Fast Switching	No	Yes	Partial	XT-estimated
Sharma *et al.* [2022]	SDM-EON	Dynamic Core	SS-DC + DS-SC	No	Yes	Yes	XT-estimated
Chatterjee *et al.* [2021]	SDM-EON	Dynamic Core	XT-aware Allocation	No	Yes	No	XT-avoid
Zhang *et al.* [2022]	SDM-EON	Dynamic Core	XT-aware Path Selection	No	Yes	No	XT-avoid
Ahmed *et al.* [2022]	SDM-EON	Dynamic Core	XT-aware Optimization	Yes	Yes	No	XT-estimated / XT-avoid
Wang *et al.* [2021]	EON	Fixed Core	MCDM Spectrum Reallocation	Yes	No	No	–
Singh *et al.* [2018]	EON	Fixed Core	Proactive / Reactive	No	No	No	–
Buffa *et al.* [2020]	EON	Fixed Core	External Frag. Metric	No	No	No	–
Wu *et al.* [2014]	EON	Fixed Core	Frag. Metric Design	No	No	No	–
This Work	SDM-EON	Dynamic Core	Slot Window Defragmentation	**Yes**	**Yes**	**Yes**	**XT-avoid**

windows prior to reallocation. This method dynamically identifies the most critical regions of fragmentation, enabling localized and efficient spectrum reorganization while balancing performance, scalability, and crosstalk mitigation. By adapting window size to traffic demands and prioritizing low-cost reallocations, WDefrag effectively addresses both vertical and horizontal fragmentation—limitations that are often insufficiently handled by traditional global or greedy defragmentation strategies. This technique was specifically designed to optimize spectral resource allocation in SDM-EON networks, where the spatial dimension introduced by multicore fibers adds significant complexity.

Slot Window Defragmentation reorganizes spectrum blocks across multiple cores and frequency slots, creating larger contiguous regions of available bandwidth to accommodate new lightpath demands. In contrast to existing methods, WDefrag explicitly accounts for both spectrum continuity and crosstalk constraints—particularly through integration with XT-avoid mechanisms—ensuring transmission quality is preserved during reallocation. As the defragmentation problem is known to be NP-complete, WDefrag adopts a heuristic-driven strategy to maintain low blocking probability and guarantee SLA compliance under dynamic and heterogeneous traffic conditions.

Our algorithm, WDefrag, is an RMSCA algorithm designed to optimize resource allocation by prioritizing the shortest routes, ensuring efficient lightpath setup through a First-fit core and spectrum allocation technique. This fragmentation-aware approach, as outlined by Sharma *et al.* [2022], incorporates both reactive and proactive defragmentation strategies via the XT-avoid technique, using the SS-DC and DS-SC methods. While WDefrag incorporates certain principles from established defragmentation techniques, its novelty lies in its Slot Window Defragmentation strategy. This technique dynamically defines localized windows along critical routes, concentrating defragmentation efforts on areas where fragmentation most affects resource availability. By reorganizing spectrum slots within these windows, WDefrag reduces computational overhead, improves local spectrum usage, and enhances multi-core coordination, thereby reducing horizontal and vertical fragmentation.

Unlike previous techniques that apply global reallocation or push-pull approaches without pre-selecting regions of interest, our strategy introduces a pre-processing step that segments the spectrum into cost-evaluated windows. This segmentation enables smarter prioritization of reallocation efforts, ensuring computational scalability and higher spectral efficiency. This procedural shift highlights the conceptual departure from conventional reallocation methods, underscoring how Slot Window Defragmentation adapts to the spatial and spectral dynamics of SDM-EONs. Additionally, WDefrag integrates the CASD-Push-pull technique from Brasileiro *et al.* [2020] to minimize defragmentation interruptions. Proactive defragmentation is feasible due to the hitless technique from Brasileiro *et al.* [2020], reducing the impact of continuous lightpath reallocation. WDefrag further refines this approach by prioritizing slot segments based on Equation 1, with dynamic window size adjustments tailored to bandwidth demands for effective resource utilization. The use of Slot Window Defragmentation in WDefrag ensures that bandwidth is efficiently allocated by reorganizing slot segments to form larger contiguous blocks, reducing fragmentation and blocking probability.

WDefrag employs the XT-avoid method to establish a logical layer that accounts for interference between neighboring channels, using this information as a constraint for connection establishment. Figure 2 illustrates the distinction between the slots used at the physical layer (PCTotal) and those available at the logical layer (LCTotal), which evaluates resource availability based on inter-core interference. In PCTotal, core 0 for Link 0 shows a mix of used slots (Slot 2) and guard bands (Slot 1), with no free slots (Slot 0) in this specific example. This illustrates a scenario where all available slots are occupied or reserved as guard bands, reflecting the challenge of limited spectral resources. LCTotal, however, refines this assessment by indicating which slots are truly available without interference from neighboring cores, particularly in cores 0, 5, and 6. For example, although PCTotal shows available slots in core 0, LCTotal reveals that some slots, particularly in cores 1, 2, and 3, are not feasible for use due to inter-core interference. LCTotal is dynamically updated with each new demand, further refining the resource allocation process. In the scenario depicted in Figure 2, even though PCTotal shows unused slots in channels 5 and 6, these slots could introduce crosstalk if used. By relying on LCTotal and the XT-avoid technique, WDefrag ensures that both reactive and proactive defragmentation processes avoid crosstalk, enabling cleaner, interference-free lightpath allocations.

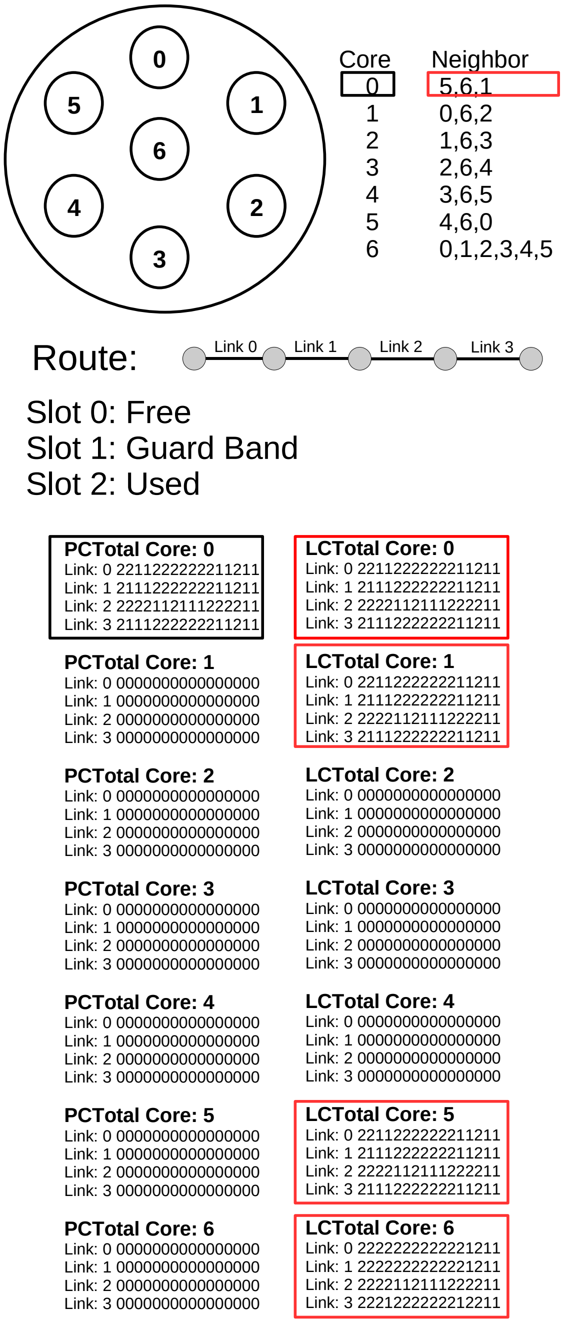

Figure 2. PCTotal x LCTotal

WDefrag offers the flexibility to perform either reactive or proactive defragmentation, depending on network conditions. Reactive defragmentation is triggered when a demand is blocked due to insufficient free capacity in the route link slots across one or more fiber cores. In contrast, proactive defragmentation is initiated whenever a new connection demand arrives, regardless of current network congestion. Both processes aim to reallocate as many slot windows as possible, where a window refers to a set of slots or a group of lightpaths. While proactive defragmentation incurs higher operational costs than reactive defragmentation, it has the advantage of postponing network congestion by continuously reorganizing fragments to optimize slot usage. This approach helps maintain high levels of network performance under increasing traffic loads.

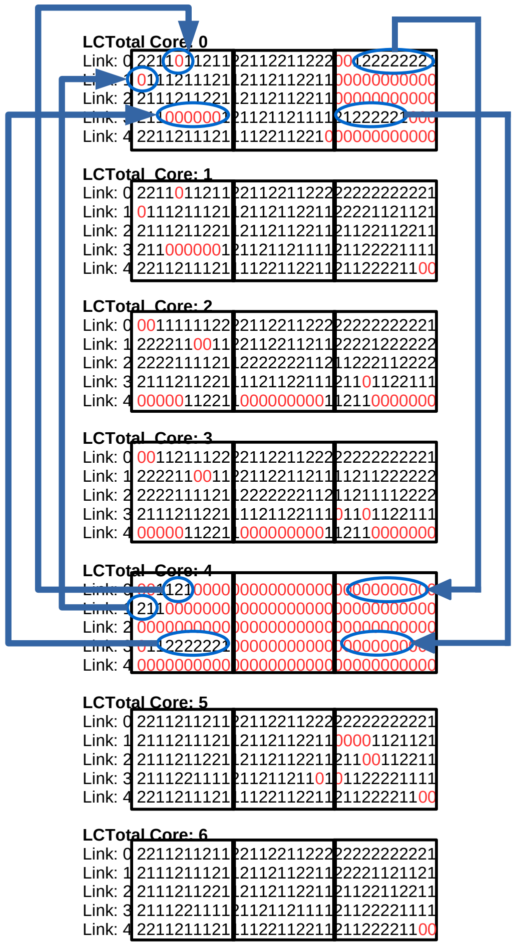

Figure 3. SS-DC Defragmemtation

All these processes follow the First-Fit allocation strategy, ensuring a unified resource organization by consistently applying the same allocation rules across the spectrum. Figures 3 and 4 further illustrate the segment window technique, where a segment window is removed from each core along the path of demand links. The First-Fit strategy typically releases initial demands on one side of the spectrum, as depicted in Figure 4. In Figure 3, an example demonstrates how a segment window is released through core exchange using the SS-DC method, which maintains the slot index and the original transponder without applying the First-Fit technique. This example shows how reallocation can lead to additional fragmentation, especially as the transfer of the third window lightpaths from core 0 increases fragmentation in core 4.

In contrast, Figure 4 illustrates the fragmentation of lightpaths across route cores and links, showing how the DS-SC technique functions. By reusing the same spectrum band, SS-DC proves to be more cost-effective than DS-SC, as it eliminates the need for an additional transponder. However, SS-DC has a higher risk of increasing fragmentation, yet this does not directly correlate with higher blocking rates. In fact, despite the increased fragmentation, SS-DC can yield more efficient results by freeing up resources more quickly and in a simpler manner, as demonstrated by our results. The constant rearrangement of the spectrum in response to demand means that fragmentation can fluctuate without necessarily impacting overall network performance. The flexibility provided by SS-DC enables rapid reallocation, which can mitigate the impact of fragmentation over time. Meanwhile, the DS-SC method focuses on defragmenting windows, clustering demands through First-Fit, and reducing core fragmentation. The DSSC reallocation uses fast switching and push-pull techniques to ensure a smooth transition of lightpaths during reallocation, as shown in Figure 4.

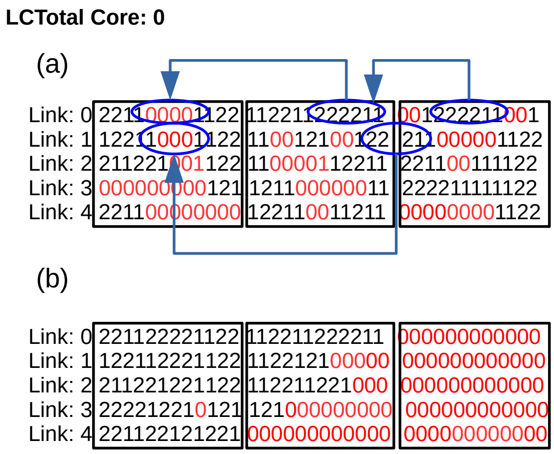

Figure 4. DS-SC Defragmemtation

The WDefrag concept aims to establish a sequence of structured spectrum windows that reduce computational effort and offer a cost-effective approach to reallocating spectrum resources. The focus is on windows containing lightpaths with fewer hops, smaller capacities, and lower quantities, which allows for more efficient reallocation. By concentrating on minimizing the number of lightpaths per window, our algorithm reduces the complexity of reallocation and limits equipment usage. Lightpaths with fewer hops require fewer modifications across the network, which in turn decreases the likelihood of contributing to spectrum fragmentation. Additionally, lightpaths with smaller capacities make it easier to identify and allocate available slots. WDefrag incorporates a sorting mechanism that organizes window segments and slots in ascending order, prioritizing those that require the least computational effort to reallocate.

Our algorithm uses Equation 1, which identifies the window with the lowest operating cost. This equation incorporates three key metrics: the number of lightpaths, the number of hops between all lightpaths, and the number of free slots. The selected window is the one that requires the least defragmentation effort, minimizing the need for transponder reconfiguration and reducing downtime during channel or slot position changes. When possible, the use of push-pull techniques Cugini *et al.* [2013] and fast switching Brasileiro *et al.* [2020] ensures that traffic disruptions are eliminated, but this depends on the availability of a free core, as illustrated in Figure 5. The presence of an available core allows for the seamless implementation of these techniques, facilitating a smooth reallocation process without service interruptions.

Figure 5. Push-pull and Fast-Switching Brasileiro *et al.* [2020]

$$F_{c_1} = \alpha_1.nLps + \alpha_2.nHops + \alpha_3.nFrees \qquad (1)$$

The variable values in Equation 1 correspond to each window stored in the list. The variable $nLps$ represents the number of lightpaths, $nHops$ stores the total number of hops across all lightpaths, and $nFrees$ refers to the number of free slots available. If $nFrees$ has a higher value, it indicates that the window has lower capacity; conversely, a lower $nFrees$ suggests higher capacity. These variables are compared against each other to establish their precedence in the defragmentation process. This comparative analysis explores the intricate relationship between these parameters, examining how they collectively influence both defragmentation efforts and the reduction of the blocking rate.

WDefrag performs defragmentation based on window size and traffic patterns. The traffic pattern employed categorizes windows by the number of slots corresponding to the capacity of each demand and adds the guard bandwidth, with 10, 20, 40, 100, and 200 Gb/s translating into 3, 4, 6, 8, and 16 slots, respectively. Each slot accommodates 12.5 Gb/s. We defined these window sizes based on a conservative BPSK modulation reference, which ensures feasibility across all path lengths. However, WDefrag does not fix modulation to BPSK during allocation. Instead, it dynamically computes the number of required slots according to the modulation supported by each path, preserving the RMSCA classification. The BPSK-based sizes serve only to guide the Slot Window Defragmentation mechanism by offering uniform, worst-case window categories for fragmentation analysis. Spectrum organization can be effectively optimized by gradually adopting vector window sizes. Our findings suggest that reallocating windows of various sizes yields the most favorable results. Empirical evidence shows that performing multiple iterations on the spectrum with varying window sizes is more efficient than relying on a single size. This iterative approach accelerates the identification of available resources. By progressively resizing windows in reallocation rounds, it becomes possible to reanalyze the new fragmented state of the route, facilitating the most optimal reallocation.

Our defragmentation strategy draws inspiration from the Tetris game Dong *et al.* [2024], where differently shaped blocks are strategically positioned to eliminate gaps and optimize space usage where different window sizes are applied to achieve the best allocation. Similarly, the Slot Window Defragmentation technique reorganizes fragmented spectrum segments using the First-fit policy to maximize contiguous free slots and reduce spectral fragmentation. In Tetris, it is necessary to reposition and rotate the pieces to optimize the filling of the board, avoiding gaps and unused spaces. Similarly, in spectrum defragmentation, windows of different sizes allow frequency blocks to be adjusted more efficiently, analyzing the different fragmentations at each stage and finding the best way to rearrange the available resources. However, unlike Tetris, which allocates pieces based on their arrival order without specific criteria, our solution reallocates resources using intelligent criteria, aiming for optimal positioning and minimizing fragmentation.

After analyzing several windows, we tested variations in the window list: ascending (3, 4, 6, 8, and 16 slots) and descending (16, 8, 6, 4, and 3 slots). Each window list is ordered based on the value of each window calculated using Equation 1. The choice between ascending and descending window sizes is related to prioritizing high- or low-throughput windows. The ascending list prioritizes windows with fewer lightpaths, while the descending list focuses on windows with more lightpaths. Different window sizes present distinct advantages and disadvantages, depending on the specific network demands and the desired balance between throughput and efficiency.

Larger windows facilitate better differentiation of window values compared to smaller windows, making it easier to identify and reallocate more lightpaths, which increases reallocation capabilities. Sorting the list by decreasing values in the equation helps identify higher-capacity lightpaths, improving resource availability after successful reallocation. Higher-capacity lightpaths often take longer to disconnect than lower-capacity ones. By deferring lower-capacity lightpaths to later stages, decreasing-order sorting makes it easier to free up the spectrum further to the right, increasing the size of free blocks and reducing fragmentation. Additionally, defragmenting larger windows during periods of lighter traffic helps prevent congestion, optimizing resource usage and avoiding bottlenecks.

Relocating smaller windows addresses fewer lightpaths and limits the differentiation of the values in Equation 1, as they make the variable $nLps$ nearly uniform. This makes it harder to identify $nFrees$, shifting the equation's priority toward lightpaths with fewer hops ($nHops$). Smaller window defragmentation, however, allows for faster resource release by targeting lower-capacity lightpaths and can yield better results during periods of high congestion. Lightpaths with shorter paths disconnect more quickly than higher-capacity ones. While smaller windows can create more fragmentation by generating numerous smaller, non-contiguous free blocks, they can also contribute to forming larger free blocks when adjacent to other free blocks, thus reducing fragmentation. The WDefrag algorithm has thoroughly examined and evaluated each of these potential outcomes.

It is important to highlight that all window lightpath reallocation processes follow LCTotal, which adopts the XT-avoid method and First-fit allocation. The algorithm's main objective is to alleviate route and network congestion, restructure available resources, and enhance larger free fragments, thereby reducing the blocking rate. By systematically reorganizing resources using these techniques, WDefrag ensures that congestion is minimized, and the spectrum is optimized for future demands. Wdefrag algorithm applies a mechanism adapted to the characteristics of SDM-EON networks. The cost-aware window evaluation considers not only the spatial distribution of available slots but also crosstalk risk, core usage, and slot continuity. This makes WDefrag scalable and effective, transforming localized actions into significant network-wide performance improvements.

4 WDefrag Algorithm

The WDefrag algorithm is designed to perform efficient spectrum defragmentation by reallocating spectrum windows according to traffic patterns, window sizes, and congestion levels. It utilizes a combination of the XT-avoid method and First-fit allocation, guided by the LCTotal metric, to ensure that lightpath reallocation avoids crosstalk and maximizes available resources. The algorithm aims to alleviate network and route congestion, improving the availability of larger free fragments and ultimately reducing the blocking rate.

In WDefrag, ascending and descending window size orders are considered for reallocation without prioritizing one over the other. Evaluating these two possibilities allows flexibility in responding to different network conditions. Larger windows can be defragmented during periods of lower traffic, facilitating the creation of contiguous spectrum blocks, while smaller windows are useful in high-congestion scenarios for quick resource reallocation. This balanced approach ensures that the algorithm adapts dynamically to varying network needs. The algorithm optimizes spectrum organization by progressively adjusting window sizes in iterative reallocation rounds, much like adjusting pieces to achieve the most efficient use of available space. The reallocation process carefully balances the number of lightpaths, hops, and available free slots, ensuring minimal disruption to traffic, and employs push-pull techniques and fast switching where possible.

WDefrag operates according to the flowchart in Figure 6. It begins by executing the RSCA (Routing, Spectrum, and Core Assignment) using the shortest path routing to determine the optimal route. After identifying the route, the algorithm defragments the selected path, ensuring efficient spectrum use. The ongoing demand is then allocated using BPSK modulation, with cores and slots chosen through the first-fit allocation method. This method handles spectrum reallocation for both horizontal defragmentation (DSSC) and vertical defragmentation (SSDC), optimizing the spectrum by reducing fragmentation in both dimensions.

Initially, the pseudocode receives as input the demand (s,d,b, T,M, a), where s denotes the source, d the destination, b the bandwidth, T represents the window size or number of slots, M indicates whether the approach is reactive (R) or proactive (P), and the variable a can be either SSDC or DSSC. The variable a controls the reallocation order, allowing WDefrag to prioritize SSDC or DSSC based on network conditions and resource availability to balance cost efficiency and performance. SSDC improves resource utilization in low-traffic scenarios by maintaining spectrum continuity along the same route, simplifying spectrum management, reducing reallocation overhead, and minimizing service interruptions—key factors that reduce operational costs.

However, SSDC's reliance on preserving the original route limits its flexibility in high-traffic conditions. In contrast, DSSC provides superior adaptability in congested networks by proactively reallocating resources across multiple routes, effectively mitigating congestion and reducing the blocking rate. While DSSC improves performance, its broader reallocation efforts can increase operational complexity and require additional resources.

The cost function defined in Equation (2) drives this adaptive behavior by evaluating fragmentation patterns, available spectrum windows, and potential reallocation costs to identify the most effective strategy for each scenario, ensuring optimal resource utilization and improved network performance. Furthermore, WDefrag is compatible with any number of transmission cores, ensuring scalability across evolving SDM-EON architectures. Its modular cost function can also be extended to incorporate new variables, such as modulation format constraints or spatial crosstalk thresholds. These properties allow WDefrag to remain effective as technologies and traffic dynamics change, offering a future-ready solution for spectrum defragmentation.

The LCTotal list covers the entire network and serves as the foundation for defragmenting the lightpath spectrum along the route corresponding to the forwarded demand. Lightpath reallocation is only possible if the same free and continuous spectrum resource is available in some of the cores and on all interconnected links that form the path. Ensuring that these unoccupied wavelength resources are accessible across the entire path is crucial for successfully relocating the lightpath. After generating the LCTotal list using $createLC()$, the pseudocode differentiates between reactive and proactive defragmentation methods based on the input M, and proceeds with the corresponding reallocation strategy.

In the reactive approach, the algorithm generates a single window vector based on the size of the blocked demand; if $M == R$, the window size T will correspond to the number of blocked demand slots, resulting in a vector with a single window size. On the other hand, if $M == P$ (proactive), the algorithm generates a vector T for all demand classes, regardless of the specific demand size. These classes can include window sizes in ascending (3, 4, 6, 8, 16) or descending (16, 8, 6, 4, 3) order. The SortWindows() function sorts the list according to Equation 1, preparing the vectors for the defragmentation process.

In the reallocation process, WDefrag assigns a priority by first using either the RealocSS() function to handle SS or the RealocDS() function for DS if the initial allocation attempt fails, and vice versa. The value of the a parameter determines the reallocation order, guiding the system to attempt one function before resorting to the other. After examining all vector windows, the algorithm completes the defragmentation by reallocating the current demand (s, d, b, T, M, a), finalizing both the defragmentation and the RSCA process.

The complexity evaluation of our algorithm follows $route = Dijkstra(s,d,k)$ with $O(K|V|(|E| + |V|Log|V|))$, where K is the number of paths, V the set of nodes and E the set of links of the network topology. $WDefrag()$ is composed of the routines CreateLC, CWindows, SortWindows, RealocDS, and RealocSS as shown

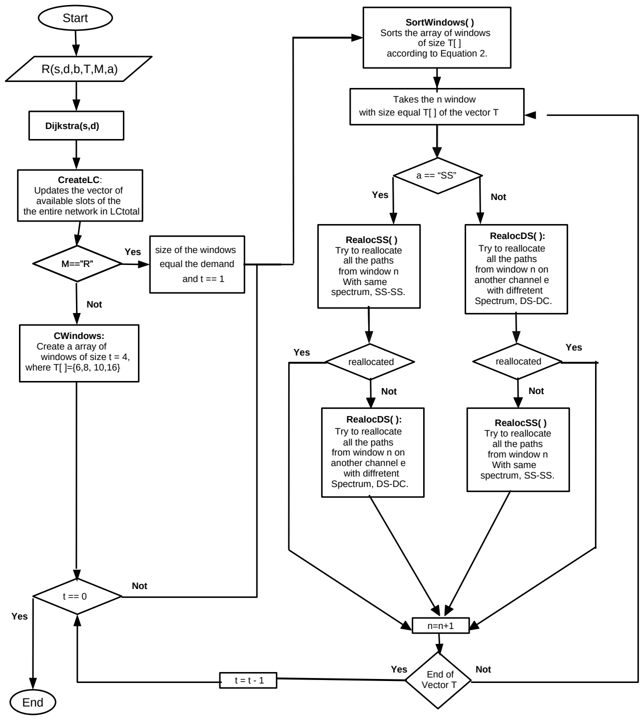

Figure 6. WDefrag Fluxogram

in Figure 6. CreateLC, which is responsible for updating the LCTotal, has $O(|E| * |C| * |S|)$, with C as the set of fiber cores and S as the set of slots. CWindows has $O(|E| * |(S/T)| * |S|)$, with T as the window size where (S/T) represents the number of windows. SortWindows sorts the slots according to Equation 1 and has a complexity of $O(|(S/T)|)$. RealocDS has $O(|(L)| * |(S/T)|)$ with L the maximum number of optical paths, and realocSS with $O(|(L) * |(S/T)|)$ with the possibility of traversing all windows in the worst case. The worst-case complexity of the whole algorithm is $O(K|V|(|E| + |V|Log|V|)) + O(|E| * |C|| * |S||)^2 + O(|E| * |(S/T))$.

5 Results

The following results demonstrate the performance of the WDefrag algorithm in handling spectrum defragmentation and resource allocation under various traffic conditions. The experiments were conducted to evaluate the efficiency of both the reactive and proactive defragmentation approaches, analyzing the impact on key metrics such as blocking probability, resource utilization, and fragmentation reduction. The results are presented by comparing the ascending and descending window sizes, as well as the priority given to SSDC or DSSC, based on the value of the a parameter.

Through detailed simulations, we assessed the algorithm's ability to reallocate lightpaths and reduce congestion, focusing on the trade-offs between different window sizes and defragmentation strategies. Additionally, the experiments reveal how WDefrag adapts to varying traffic loads, ensuring efficient spectrum utilization even during peak demand periods. The results provide insights into the advantages of employing the XT-avoid method, First-fit allocation, and dynamic window resizing, highlighting their combined impact on overall network performance.

The graphs presented compare our model with the CASD-Push-Pull proactive defragmentation algorithm Brasileiro *et al*. [2020], XT-estimated reallocation, and the Baseline, which does not use defragmentation or reallocation. Simulations were carried out using the ONS optical network simulator Costa L. e Sousa L. e Oliveira F. e Silva K. e Souza P. e Drummond [2016], considering the USANet topology with 24 nodes and 43 bidirectional links, and the PanEuro topology with 27 nodes and 82 bidirectional links (Figure 7). Each simulation processed 100,000 connection requests under different network load levels, measured in Erlang. The load was calculated as the average arrival rate multiplied by the call duration and bandwidth, normalized by the link capacity (10 Gbps). To ensure robust results, we employed the independent replication method, running each simulation five times with different seeds and computing 95% confidence intervals.

Our primary goal is to achieve a balance between external fragmentation and blocking rate. Connection requests followed a Poisson process with an average retention time of 600 seconds, uniformly distributed among all node pairs. Each link provided 4000 GHz of capacity, totaling 320 slots of 12.5 GHz per fiber, and demands ranged from 10 to 200 Gb/s (1 to 16 slots). In addition, we allocated 2 guard band slots per unidirectional fiber, used BPSK modulation, and addressed the RSCA problem with uniform traffic distribution.

These results demonstrate the advantages of the reactive and proactive process specifications, SSDC and DSSC reallocations, varying window sizes, and their impact on fragmentation. Our primary reference is the blocking rate, targeting the 5% range, which aligns with standards in the existing literature. The WDefrag algorithms present these variations and utilize the XT-avoid technique. The proactive algorithms, WDefragDecresc and WDefragCresc, defragment whenever a demand arises, while the reactive algorithm, WDefragReactive, triggers defragmentation only when a demand is blocked. WDefragDecresc employs windows of 18, 10, 6, 4, and 3 slots, while WDefragCresc uses 3, 4, 6, 10, and 18 slots. WDefragReactive adapts window sizes according to the demand.

The DSSC method combines Push-pull and Fast-Switching techniques with First-fit, used in WdefragDecrescDSSS and WdefragReactiveDSSS, while SSDC involves only core exchanges, as seen in WdefragDecrescSSDC and WdefragReactiveSSDC. The window sizes are aligned with demand patterns in terms of the number of slots, and defragmentation is applied exclusively to the requested route.

5.1 Blocking Rate and Bandwidth Blocking Rate

Blocking Rate (BR) and Bandwidth Blocking Rate (BBR) are two key metrics used to evaluate network performance in terms of connection establishment and resource allocation. BR measures the percentage of connection requests that are blocked or fail to be established within the network, offering a general view of how well the network handles connection

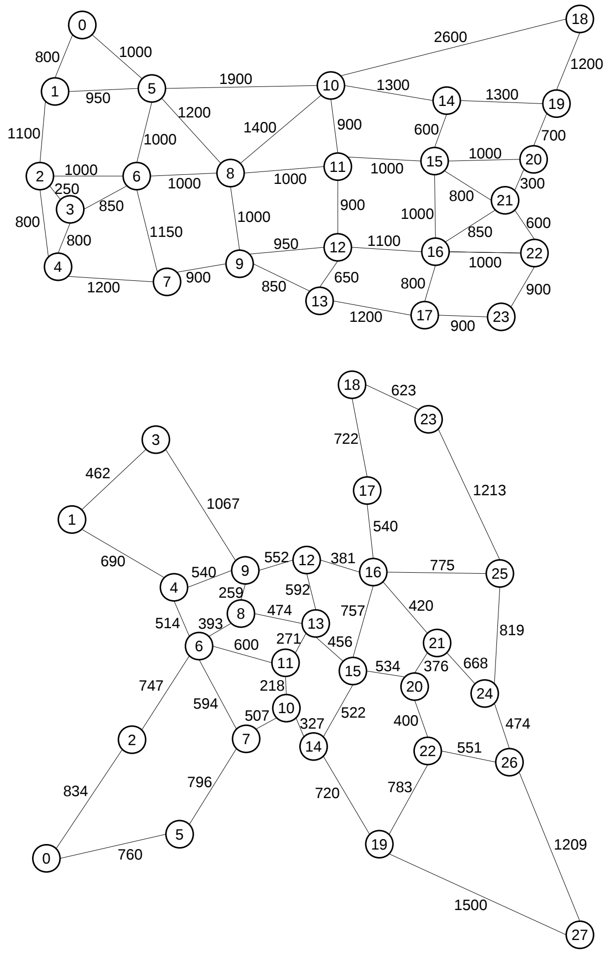

Figure 7. USANet and Paneuro Network

requests. On the other hand, BBR measures the percentage of bandwidth that remains unallocated for connection requests or, more specifically, the ratio of total blocked bandwidth to the total requested bandwidth. While BR provides an overall measure of the network's capacity to accept connections, BBR offers a more detailed analysis of bandwidth allocation efficiency.

Figures 8, 9, 10 and 11 demonstrate the effectiveness of window defragmentation with XT-avoid compared to the CASD-Push-Pull algorithm Brasileiro *et al*. [2020] using XT-Estimated. In terms of metrics, BR gives a more equal perspective by treating all demands similarly, regardless of their size. However, BBR presents a more nuanced analysis, where higher-capacity demands have more weight compared to lower-capacity ones. As a result, higher-capacity demands are more likely to be blocked, and their impact on the overall blocking rate is greater than that of lower-capacity demands.

Figure 8 illustrates the relationship between traffic load, measured in Erlang (x-axis), and the blocking ratio (BR) on the y-axis in the USANet topology, focusing on the 3,500 Erlang range. The Baseline algorithm shows the highest BR at 6.65%, while the CASD-PushPull improves slightly with a BR of 6.58%, offering a minimal gain of 1.05% relative to the Baseline. Among the Wdefrag strategies, WdefragCrescSSDS achieves the lowest BR at 5.14%, providing a substantial improvement of 21.88% over CASD-PushPull. Similarly, WdefragDecrescSSDS performs well, with a BR of 5.08%, reflecting a gain of 22.78% over CASD-PushPull.

Additionally, it is important to note that both WdefragDecrescSSDS and WdefragCrescSSDS achieve a blocking rate of 5% at 3,500 Erlangs, whereas CASD-PushPull reaches this same blocking rate at 3,000 Erlangs. This means that WdefragDecrescSSDS and WdefragCrescSSDS can handle approximately 18% more traffic load than CASD-PushPull before reaching the 5% blocking threshold. Other strategies, such as WdefragReativoDSSS and WdefragCrescDSSS, also show improvements, with BR reductions of 6.31% (4.10% better than CASD-PushPull) and 6.20% (5.77% better than CASD-PushPull), respectively. These results confirm that Wdefrag strategies, especially the SSDS variants, are highly effective in reducing bandwidth blockage in highly connected topologies like USANet. For network operators, implementing WdefragDecrescSSDS or WdefragCrescSSDS would lead to better resource allocation, reduced network congestion, and improved quality of service.

The proactive defragmentation approach, combined with the SSDC method, consistently delivers the best results in reducing blocking rates and fragmentation. Additionally, the use of decreasing window sizes provides a slight improvement in performance, further optimizing the spectrum allocation. These strategies demonstrate superior efficiency in handling high traffic loads while minimizing the impact on network resources.

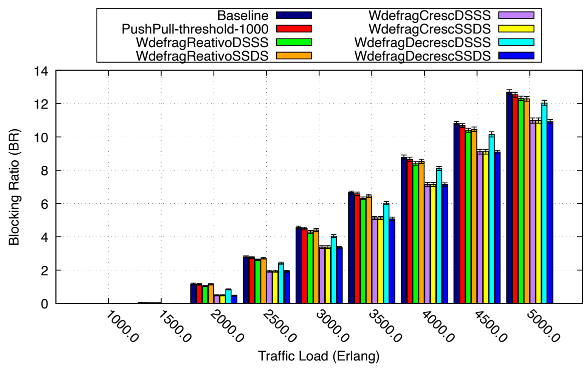

Figure 8. BR on USANet Network

Figure 9 illustrates the BBR in the USANet topology in the 2,500 Erlang range with WdefragDecrescSSDS as reference for having a result close to 5%. The Baseline algorithm demonstrates the highest BBR of 7.38%, whereas it is now defragmented. The CASD-PushPull strategy presents a slight improvement, achieving a BBR of 7.29%, which translates to a gain of 1.23% relative to the Baseline. Among the Wdefrag variants, the WdefragCrescSSDS emerges as the best performer delivering the BBR of 5.20%, representing a substantial improvement of 28.67% compared to the CASD-PushPull. WdefragDecrescSSDS has the best BBR with 5.18%, reflecting a gain of 28.91% over CASD-PushPull. Other strategies, such as WdefragReativoDSSS and WdefragCrescDSSS, also showed improvements with BBRs of 6.94% (4.81% better than CASD-PushPull) and 6.21% (14.83% better than CASD-PushPull), respectively. These results confirm the effectiveness of Wdefrag, especially the SSDS variants.

The WdefragDecrescSSDS algorithm achieves a BR improvement of 21.88% and a BBR improvement of 28.67%, with BBR outperforming BR due to the prioritization of light-

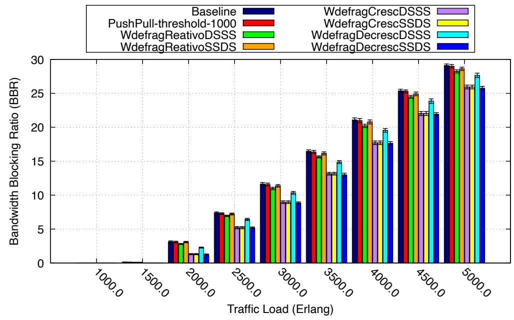

Figure 9. BBR on USANet Network

path capacity in the equation. This prioritization allows the algorithm to handle higher-capacity lightpaths more efficiently, leading to better optimization of bandwidth utilization and resulting in a more significant reduction in BBR compared to BR.

Figures 10 and 11 pertain to the PANEURO topology. Despite PANEURO being more restrictive, the results are remarkably similar to those observed in the USANet topology, which has a higher degree of connectivity. While USANet provides more routing options and potentially greater flexibility in traffic management, the defragmentation strategies in both topologies exhibit the same behavior patterns. These strategies effectively address connectivity challenges, even in a constrained network like PANEURO. By leveraging these approaches, we can enhance the network's ability to maintain reliable connections and optimize overall performance, despite the limitations posed by a more restrictive topology.

Figure 10 illustrates the BR in the PANEURO topology in the 3,000 Erlang range with WdefragDecrescSSDS as reference for a result close to 5%. Figure 10 highlights the low performance of the Baseline algorithm, with a mean BR of 7.68%, which does not perform defragmentation. The CASD-PushPull algorithm continues to perform well with a BR of 7.58%, achieving a gain of 1.30% over the Baseline. The Wdefrag algorithms demonstrate significant improvements. The WdefragCrescSSDS algorithm achieved a BR of 5.96%, representing an improvement of 21.36% compared to CASD-PushPull. WdefragCrescDSSS and WdefragDecrescDSSS achieved BRs of 7.06%, slightly better than CASD-PushPull but not as impressive as their SSD counterparts. WdefragReativeDSSS atinge BR of 7.36%, providing a gain of 2.9% over CASD-PushPull. The findings show that as the complexity of major lightpath realignment increases, the WdefragDecresc strategies, especially with SSDS, effectively lower blocking rates in high-traffic situations.

Figure 11 illustrates the BBR in the PANEURO topology in the 2,000 Erlang range with WdefragDecrescSSDS as reference for a result close to 5%. Figure 11 illustrates the BBR results for the most recent evaluation in the grid scenario. The Baseline algorithm shows a BBR of 6.31%, indicating high bandwidth locking levels due to the absence of defragmentation mechanisms. CASD-PushPull follows suit with a BBR of 6.19%, offering a slight improvement of 1.88% relative to baseline. Among the Wdefrag strategies, WdefragCrescSSDS achieved the best results with a BBR of 4.22%, reflecting a significant improvement of 31.77%

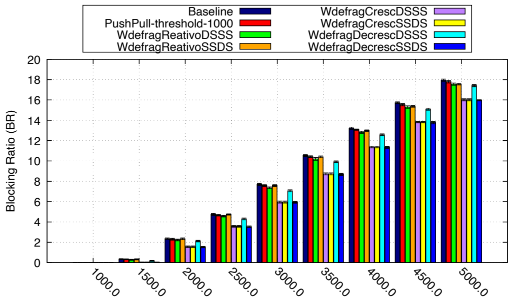

Figure 10. BR on PanEuro Network

in comparison with CASD-PushPull. Similarly, WdefragDecrescSSDS offers impressive results, with a BBR of 4.12%, representing an improvement of 33.42% in relation to CASD-PushPull. Other variants of Wdefrag, such as WdefragReativoDSSS and WdefragCrescDSSS, showed notable improvements with BBRs of 5.96% (3.4% better than CASD-PushPull) and 5.69% (8.4% better than CASD-PushPull), respectively. In real-world scenarios, such as for network operators and service providers, adopting the Wdefrag strategies, especially WdefragDecrescSSDS, can lead to substantial operational benefits. The ability to significantly reduce the bandwidth blocking rate translates into fewer rejected service requests and better resource utilization, ultimately leading to better quality of service (QoS) for end users. For operators, this means less need for capacity expansion and more efficient use of existing infrastructure. However, it is essential to balance load distribution and ensure that infrastructure is adequately sized to handle peak demand, as even the best defragmentation strategies will face challenges in extremely congested networks.

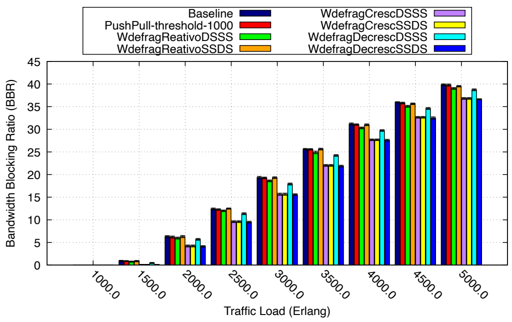

Figure 11. BBR on PanEuro Network

In the PANEURO topology, the WdefragDecrescSSDS algorithm has a very similar behavior to that in the USANet topology where it achieves a BR improvement of 21.36% and a BBR improvement of 31.77%, with an even better performance despite PANEURO being more restrictive.

5.2 External Fragmentation

This section compares external fragmentation across the network. We applied the fragmentation calculation approach proposed by Rosa et al. Rosa *et al.* [2012], adapting it to better suit the specific complexities and challenges of SDM-EON networks.

$$FragExt = 1 - \frac{largestFreeBlock}{totalFree} \tag{2}$$

While traditional EON networks typically focus on single-core resources, SDM-EON networks require a broader analysis across multiple cores. Thus, we extended this metric to consider the sum of slots across all cores within a link, providing a more comprehensive understanding of fragmentation in SDM-EON environments. Equation (2) from Rosa *et al.* [2012] calculates external fragmentation, where "largestFreeBlock" represents the number of slots in the largest contiguous free space, and "totalFree" refers to the total number of available slots. When $FragExt$ is close to one, the channel is highly fragmented, consisting of many smaller free blocks. This method emphasizes that the greater the number of small free spaces in the link slots, the higher the fragmentation. By reallocating active frequency slot fragments using the first-fit technique based on window sizes, this approach increases the probability of enlarging the "largestFreeBlock" and reducing "totalFree," thus effectively reducing fragmentation.

The complexity of resolving fragmentation in SDM networks is particularly high due to multi-core parallelism and increasing spectrum demands. Fragmentation is measured by averaging across all network links using Equation (2). As shown in Figure 12, the results are closely aligned across the evaluated algorithms. WDefrag limits defragmentation to specific routes where fragmentation critically impacts allocation. This decision avoids the excessive complexity, service disruption, and reconfiguration overhead that global reallocation typically imposes. Instead of attempting to reorganize the entire spectrum, WDefrag reallocates locally to maintain scalability and operational efficiency. Fully defragmenting the network would be impractical due to prolonged downtime and equipment overhead. In contrast, route-based defragmentation offers a practical, cost-effective solution aligned to maximize performance while minimizing expenses.

When WDefrag reallocates resources along a given route, it may misalign or scatter spectrum on overlapping lightpaths—a phenomenon known as external fragmentation. Despite this side effect, the trade-off proves beneficial: reducing the blocking rate directly lowers the risk of SLA violations and yields measurable performance gains, as demonstrated in Figures 8 to 11. In SDM-EON networks, attempting to reduce fragmentation globally can increase complexity without necessarily improving performance Amar *et al.* [2015]. Because lightpaths from different source-destination pairs often share common links and cores, each reallocation impacts other paths and contributes to overall external fragmentation. Nonetheless, this route-focused defragmentation improves resource availability on critical paths, reduces the blocking rate, and enhances bandwidth utilization.

This tradeoff between fragmentation and blocking rate is central to our approach. WDefrag intentionally prioritizes reducing the blocking rate over minimizing external fragmentation. Although fragmented spectrum may remain in less congested areas of the network, the algorithm focuses on reallocating slots along critical, high-demand routes. In SDM-EONs, ensuring resource availability along these routes yields a higher practical gain than attempting to maintain uniform spectrum continuity across the entire network. This design choice leads to localized improvements in resource allocation that significantly reduce the blocking rate, as shown in Figures 8 to 11, even if overall external fragmentation increases, as seen in Figure 12. By balancing these factors, WDefrag offers a pragmatic solution tailored to real-world performance constraints in SDM-EON environments.

Figure 12 compares the external fragmentation of the entire network and shows that most algorithms that perform route-based defragmentation tend to increase fragmentation across the network. As observed, only WdefragReativoDSSS and WdefragDecrescDSSS achieve better results than Baseline, which does not apply any defragmentation. Algorithms using the SSDC method tend to increase fragmentation when changing lightpaths between cores without altering the spectrum. However, they are more effective in high-demand networks regarding blocking ratio (BR) and bandwidth blocking ratio (BBR). On the other hand, DSSC algorithms reduce external fragmentation by consolidating free blocks on a single core but face challenges in accommodating new traffic, which leads to increased blocking rates. This tradeoff illustrates the complexity of choosing allocation strategies, balancing minimizing external fragmentation and reducing blocking rates.

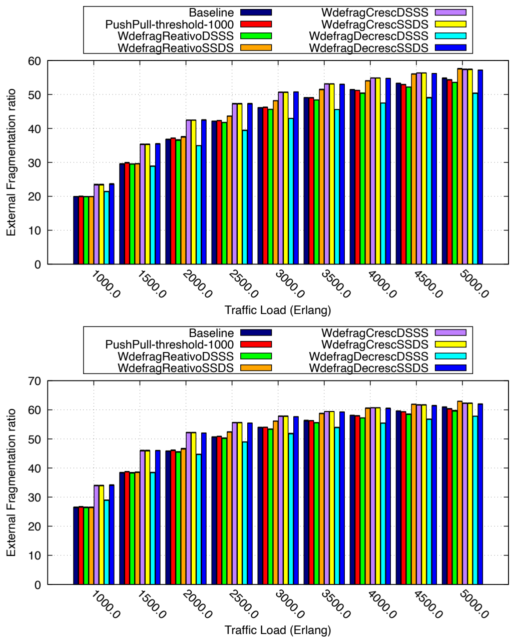

Figure 12. External Fragmentation on USANet and PanEuro Network

Figure 13 compares the average route fragmentation in the network and shows that, unlike external fragmentation, most algorithms that perform route-based defragmentation reduce fragmentation along the routes. All defragmentation algorithms have significantly lower fragmentation levels than Baseline, which performs no defragmentation. This reversal in results compared to external fragmentation highlights the complexity of route defragmentation strategies, where focusing on minimizing route fragmentation can lead to increased external fragmentation.

In summary, while route-based defragmentation strategies are effective in reducing fragmentation along specific routes, they often come at the cost of increased external fragmentation. This is particularly evident when lightpaths are reallocated across multiple links, impacting the network-

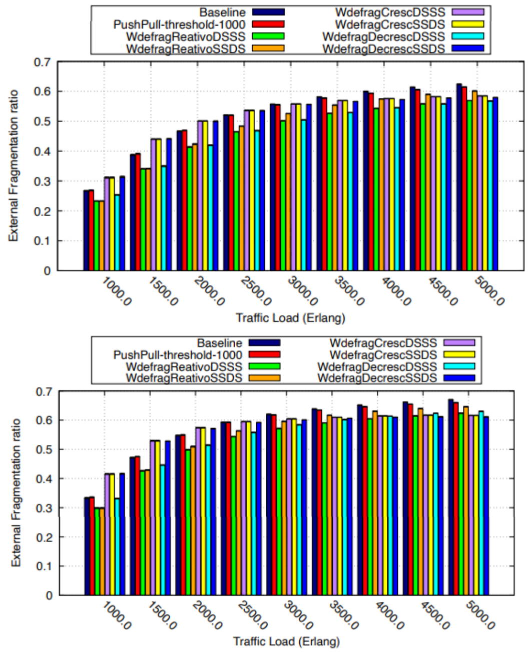

Figure 13. Mean Route Fragmentation on USANet and PanEuro Network

wide spectrum. Algorithms that employ the SSDC method, though prone to increased external fragmentation, demonstrate higher effectiveness in networks with high traffic demands, as they prioritize reducing blocking rates. On the other hand, DSSC algorithms are more successful in minimizing external fragmentation but struggle with higher blocking rates. These findings highlight the inherent trade-offs between optimizing for route-specific defragmentation and managing network-wide fragmentation, underscoring the importance of selecting the appropriate strategy based on specific network requirements and traffic conditions.

6 Conclusion

The WDefrag algorithm offers a novel solution for spectrum defragmentation in SDM-EON optical networks, delivering substantial gains in performance and cost-effectiveness. By strategically managing spectrum resources through "spectrum windows" (contiguous available blocks), WDefrag optimizes allocation and minimizes fragmentation.

Its integrated proactive and reactive defragmentation strategies allow dynamic adaptation to traffic, ensuring high spectrum utilization and preventing congestion. A key innovation is the incorporation of the XT-avoid technique alongside a cost equation and defragmentation window management. This proactively mitigates crosstalk during lightpath setup, improving signal integrity—a clear advantage over reactive methods like the greedy XT-Estimated technique, which often compromise long-term spectrum efficiency.

WDefrag also drives down operational costs. Prioritizing reallocation along the same route minimizes disruptive reconfigurations, leading to lower latency and enhanced stability. Its cost-equation-driven reallocation optimizes resource use based on path length and availability, increasing the network's capacity to accommodate traffic growth and potentially delaying expensive upgrades.

Ultimately, WDefrag provides a robust framework for improving resource allocation, signal quality, and overall QoS in SDM-EON networks while reducing costs. Future enhancements include dynamic adaptation between SSDC and DSSC reallocation modes, equipping WDefrag with greater operational intelligence to respond to real-time network conditions.

Declarations

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Authors' Contributions

The author **Paulo José de Souza Júnior** contributed to the conception of this study, analysis, and writing. He is the main contributor and writer of this manuscript. The author **Lucas Rodrigues** and the author **Marcelo Antonio Marotta** participated in the validation of the study, review, and final editing. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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