DeRA: Defragmentation-Aware Resource Allocation with Counter-Propagation in Spectrally-Spatially Elastic Optical Networks

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***Abstract*—Spectrally-spatially elastic optical networks (SS-EONs), integrating elastic optical networks with space-division multiplexing technologies such as multi-core and multi-mode fibers, have emerged as a key enabler to enhance network capacity and flexibility. However, efficient routing, spectrum, core, and mode assignment in SS-EONs remain a major challenge due to inter-core XT, inter-mode XT, and spectrum fragmentation. Counter-propagation, where signals in adjacent cores and modes propagate in opposite directions, has shown promise in mitigating XT and improving spectral efficiency under asymmetric traffic conditions. Nevertheless, existing counter-propagation schemes overlook fragmentation, which significantly degrades network performance in dynamic traffic environments. To address this issue, this paper proposes a defragmentation-aware resource allocation scheme, named DeRA, which jointly manages XT and spectrum fragmentation in counter-propagation-enabled SS-EONs. DeRA operates in two phases: (i) a bipartite graph-based optimization partitions the core–mode space into two disjoint sets to minimize mutual interference between counter-propagating signals, and (ii) a reactive defragmentation mechanism reorganizes spectrum resources whenever a lightpath request is blocked due to spectrum fragmentation.**

Simulation results demonstrate that DeRA achieves lower blocking probability and higher spectral efficiency compared to existing counter-propagation approaches that do not consider defragmentation.

***Index Terms*—Space division multiplexing, counter-propagation, elastic optical network, crosstalk, defragmentation.**

I. INTRODUCTION

The continuous surge in high-bandwidth services such as cloud computing, ultra-high-definition (UHD) video streaming, and large-scale machine learning applications has led to a drastic increase in data traffic across optical backbone networks. To accommodate this exponential growth, next-generation optical infrastructures must deliver high spectral efficiency, large transmission capacity, and flexible resource management. In this context, spectrally-spatially elastic optical networks (SS-EONs) have emerged as a promising paradigm that integrates elastic optical networks (EONs) with space-division multiplexing (SDM) technologies such as multi-core multi-mode fibers (MCMMFs) [1]. By extending elasticity from the spectral domain to the spatial domain, SS-EONs offer multi-dimensional scalability and significantly improved traffic admissibility.

However, routing, spectrum, core, and mode assignment (RSCMA) in SS-EONs remains a challenging task under dynamic traffic conditions, primarily due to inter-core and inter-mode crosstalk (XT) and spectrum fragmentation. XT arises from signal coupling between neighboring cores and modes, while fragmentation results from the continuous establishment and teardown of heterogeneous lightpath requests, leaving spectrum resources scattered into non-contiguous slots. Two major approaches, which are XT-avoided and XT-aware, are commonly employed to mitigate XT. The XT-avoided strategy proactively prevents spectrum allocation in adjacent cores or modes for different lightpaths, simplifying XT estimation and ensuring isolation. Conversely, the XT-aware approach allows simultaneous allocation across neighboring cores or modes as long as the XT level remains below a predefined threshold, thereby improving traffic admissibility. However, both strategies exhibit limitations in co-propagation scenarios, where signals in adjacent cores propagate in the same direction, intensifying inter-core XT and degrading system performance.

To overcome these limitations, the counter-propagation technique has been introduced, wherein signals in adjacent cores propagate in opposite directions, thereby significantly reducing inter-core XT. While traditional optical systems generally employ co-propagation to support symmetric traffic, emerging applications such as smart cities, data centers, and cloud networks are increasingly characterized by asymmetric traffic patterns. Counter-propagation effectively adapts to such traffic asymmetry by allocating different cores in multi-core fibers for each transmission direction based on actual traffic demand, thus enhancing spectral efficiency and mitigating XT.

Resource allocation in SS-EONs under counter-propagation, however, is inherently more complex than in co-propagation, as it requires independent coordination of spectrum, core, and mode assignments for the forward and backward directions of each bidirectional lightpath [2]. In co-propagation, lightpaths generally share a common physical route and are symmetrically assigned, simplifying the allocation process [3]. In contrast, counter-propagation decouples forward and backward transmissions, offering greater flexibility but substantially enlarging the allocation search space and increasing computational complexity. Moreover, counter-propagation introduces node design challenges, as both transmitters and receivers must coexist within the same fiber. This demands more intricate transceiver configurations and flexible switching fabrics capable of handling bidirectional signal routing across

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heterogeneous core–mode combinations, as the directional uniformity assumption in co-propagation no longer applies. Several recent studies have explored potential solutions for these node- and transceiver-level challenges [4], [6], [7].

Prior works on counter-propagation have addressed the RSCMA problem using integer linear programming (ILP) formulations and heuristic algorithms to optimize bidirectional core distribution and traffic admissibility [4], [8]. Analytical XT models and XT-aware allocation frameworks have also been proposed to reduce the computational complexity of online XT estimation. These studies collectively demonstrate that counter-propagation effectively lowers blocking probability and enhances overall network efficiency [10].

Despite these advances, spectrum fragmentation in dynamic SS-EON environments remains largely unaddressed. As diverse lightpath requests arrive and depart, the spectrum becomes fragmented into small, disjoint segments that cannot accommodate new high-bandwidth requests, even when sufficient total capacity exists across multiple cores and modes. This leads to higher blocking probabilities and inefficient spectrum utilization. Defragmentation techniques aim to reorganize the occupied spectrum to consolidate free slots into larger contiguous segments. Approaches such as make-before-break and hitless defragmentation allow this reorganization without service disruption. For instance, Talebi *et al.* [5] demonstrated hitless spectrum migration by establishing new lightpaths before releasing the old ones, ensuring uninterrupted service continuity.

Recent research has extended these concepts to joint spectral-spatial defragmentation in SS-EONs [11], [12] and explored traffic- and fragmentation-aware reconfiguration strategies for SDM-enabled elastic optical networks [8], [9]. However, existing defragmentation techniques are designed primarily for co-propagation systems. They cannot be directly applied to counter-propagation scenarios, where the opposing transmission directions across adjacent cores alter interference patterns, resource continuity constraints, and fragmentation dynamics. To the best of our knowledge, no prior work has addressed defragmentation mechanisms in counter-propagation-enabled SS-EONs, raising a key research question: How can spectrum defragmentation be effectively performed in SS-EONs with counter-propagation while simultaneously managing XT and maintaining high traffic admissibility?

To address the question, this paper proposes a defragmentation-aware resource allocation scheme, named DeRA, to suppress fragmentation in SS-EONs while managing XT under counter-propagation conditions. DeRA operates in two phases: (i) bipartite graph-based optimization, which partitions the core-mode space into two disjoint sets to minimize mutual interference between counter-propagating signals, and (ii) reactive defragmentation-based resource allocation, which uses these partitions as allocation parameters and triggers defragmentation dynamically whenever a lightpath request is blocked due to spectrum fragmentation. Simulation results demonstrate that DeRA significantly outperforms conventional counter-propagation schemes that do not incorporate defragmentation, achieving lower blocking probability and improved spectral efficiency.

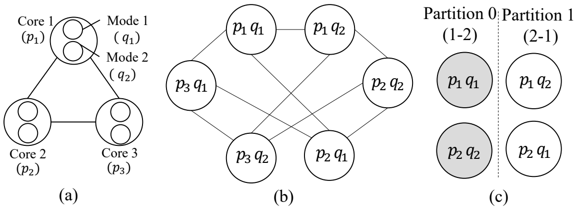
II. MODEL AND ASSUMPTIONS

The optical network is represented as a directed graph $G(V,E)$, where V is the set of nodes and E is the set of fiber links. Each link consists of a pair of fibers, each supporting lightpath transmission in both directions. The auxiliary graph is derived from the MCMMF's structure, wherein adjacency relationships are determined using well-established XT models [15]. Two vertices are designated as adjacent when the predicted XT surpasses the operator-defined threshold; conversely, they remain non-adjacent when this condition is not met. The models prohibit identical spectrum assignments across adjacent cores and modes whenever the computed XT exceeds the threshold, thereby effectively mitigating physical layer impairments. We define an undirected graph $G_A(V_A,E_A)$, where the set of vertex $V_A = p_i q_j | p_i \in P, q_j \in Q$, $|V_A| = |P||Q|$ represents all core and mode combinations. Two vertices $p_{i_1} q_{j_1}, p_{i_2} q_{j_2} \in V_A$ are connected by an edge in E_A, if the inter-core or inter-mode XT between them exceeds a predefined auxiliary threshold. The degree of a vertex $p_i q_j \in V_A$ is the number of its adjacent vertices in G_A. Each mode $q_j \in Q$ is associated with a set of spectrum slots $R = \{r_1, r_2, \ldots, r_{|R|}\}$. An individual slot is denoted by $r_s \in R$, where $s = 1,2,3,\cdots|R|$. For spectrum allocation, the same slot r_s cannot be simultaneously assigned to two adjacent vertices in G_A, while reuse across non-adjacent vertices is permitted since their XT is negligible.

The following assumptions are considered. In the optical network, two adjacent nodes are connected by a pair of fibers (the forward fiber and backward fiber), each supporting bidirectional lightpath transmission. Each optical node can switch signals between the two fibers. Each lightpath request has a specified route, direction, and spectrum capacity. All fiber links are assumed to have the same number of cores, each core contains the same number of modes, and each mode supports an equal number of spectrum slots. A lightpath is established to follow inter-core and inter-mode XT constraints, as well as spectrum contiguity, core continuity, mode continuity, and spectrum continuity constraints.

III. DERA: PROPOSED SCHEME

This section presents the proposed DeRA scheme, which operates in two sequential phases. In Phase I, resources (cores and modes) are identified for counter-propagation. We use an ILP-based bipartitioning approach with vertex elimination to divide core–mode pairs into two partitions: one used for co-propagation and the other for counter-propagation. These optimized partitions are then utilized in Phase II for resource allocation, where reactive defragmentation is triggered whenever a lightpath request fails due to spectrum fragmentation. If defragmentation successfully consolidates a feasible set of slots, the request is allocated; otherwise, it is blocked.



(a) (b) (c)

Fig. 1: Fiber structure with 3-core 2-mode, (b) auxiliary graph with core-mode adjacency, (c) bi-partitioning via vertex elimination.

A. Phase I: Resource identification for counter-propagation using ILP

This section presents how resources (cores and modes) are identified for counter-propagation by adopting the approach described in [4]. For this purpose, we define an optimization problem, referred to as the resource identification problem, with the objective of minimizing the number of eliminated vertices. This is equivalent to maximizing the number of vertices retained in the resulting bipartite graph. Such a formulation ensures efficient utilization of cores and modes while preventing inter-core and inter-mode XT.

The decision variables used in the optimization problem are defined as follows. z_a is a binary variable that equals 1 if vertex $a \in V_A$ is eliminated and 0 otherwise. x_a equals 1 if vertex a is assigned to Partition 1, and 0 otherwise. y_{ab}^{k} equals 1 if both vertices $(a,b) \in V_A$ belong to partition $k \in 0,1$.

The ILP formulation is defined as in [4]:

$$\min \sum_{a \in V_A} z_a, \tag{1a}$$

$$\text{s.t. } x_a + x_b \geq y_{ab}^{0} + y_{ab}^{1}, \quad \forall (a,b) \in E_A, \tag{1b}$$

$$y_{ab}^{0} \geq 1 - z_a - z_b, \quad \forall (a,b) \in E_A, \tag{1c}$$

$$y_{ab}^{1} \geq x_a + x_b - 1, \quad \forall (a,b) \in E_A, \tag{1d}$$

$$x_a, z_b, y_{ab}^{0}, y_{ab}^{1} \in \{0,1\}, \quad \forall a \in V_A, (a,b) \in E_A. \tag{1e}$$

The objective function in (1a) minimizes the number of eliminated vertices, thereby maximizing the available resources for spectrum allocation. Constraint (1b) enforces that if an edge (a,b) connects two vertices assigned to the same partition, then at least one of the two vertices must be eliminated in order to obtain a valid bipartite structure. Constraints (1c) and (1d) activate the partition-indicator variables; if both a and b are assigned to Partition 0, then $y_{ab}^{0} = 1$; if both are assigned to Partition 1, then $y_{ab}^{1} = 1$. Finally, constraints (1e) specify the binary nature of all decision variables. By solving this ILP, a bipartite graph is obtained as follows: if $(x_a = 0, z_a = 0)$, vertex a is placed in partition 0; if $(x_a = 0, z_a = 1)$, it is placed in partition 1; and if $z_a = 1$, vertex a is eliminated. This guarantees that the resulting graph is bipartite while minimizing the number of removed vertices.

We consider an MCMMF comprising three cores, each supporting two modes, as depicted in Fig. 1(a). An auxiliary graph is constructed by combining cores and modes according to an auxiliary threshold, as illustrated in Fig. 1(b). Applying bipartitioning approach to this auxiliary graph yields partitions 1 and 0, as shown in Fig. 1(c). Partition 0 contains vertices corresponding to core–mode combinations p_1q_1 and p_2q_2, and partition 1, contains p_1q_2 and p_2q_1. Partition 0 carries signals in the co-direction (1–2), whereas partition 1 carries signals in the counter-direction (2–1).

B. Phase II: Resource allocation along with defragmentation

This section presents DeRA, a scheme for allocating lightpaths in both directions through counter-propagation and defragmentation, aiming to enhance traffic admissibility in the network. DeRA employs a bipartitioning approach that divides cores and modes into two distinct sets, which are utilized in a counter-propagation manner for lightpath allocation. In this scheme, since signals are transmitted in opposite directions, bipartitioning is used to separate the cores and modes into two partitions only. Each element within a distinct set formed by bipartitioning is non-adjacent to the others, thereby mitigating inter-mode and inter-core crosstalk.

A lightpath can traverse both forward and backward directional fiber links. In forward fiber, vertices in partition 0 and partition 1 are assigned to lightpaths in the forward and backward directions, respectively. Conversely, in the backward fiber, vertices in partition 0 and partition 1 are assigned to lightpaths in the backward and forward directions, respectively.

DeRA also performs reactive defragmentation when a lightpath request fails due to spectrum fragmentation. By employing DeRA, the number of crosstalk-avoided, unutilized, and fragmented slots can be significantly reduced, thereby improving traffic admissibility in the network.

An example illustrating lightpath allocation and defragmentation using DeRA is shown in Fig. 2. The demonstration depicts spectrum allocation and defragmentation in the MCMMF network considering counter-propagation. As shown in Fig. 2(a), the network consists of four nodes interconnected by optical links. We consider 15 lightpath requests (LR1–LR15), which are given as follows (route, number of required slots): (1–2–3–4, 2), (2–3, 2), (4–1–2–3, 1), (3–2, 1), (3–2–1, 3), (1–2–3–4, 2), (1–2–3–4, 2), (4–1, 4), (2–4, 4), (4–3, 2), (4–1–2–3, 4), (1–2, 3), (1–2–3, 3), and (1–2–3, 2), respectively. When lightpath allocation is performed without defragmentation (Fig. 2(b)), 14 requests are successfully allocated. When defragmentation is applied, all 15 requests are accommodated (Fig. 2(c)); reactive defragmentation is triggered when LR15 is blocked, allowing it to be successfully allocated.

IV. PERFORMANCE EVALUATION

We evaluate DeRA in terms of blocking probability and traffic admissibility and compare it with conventional schemes. Blocking probability is defined as the ratio of blocked requests to total requests. Simulations are conducted on two topologies: the NSF network [18] and the Japanese network [4], as shown in Fig. 3(a) and (b), respectively. For each link, we employ an MCMMF consisting of 7 cores and 6 modes, resulting in 42 spatial channels. Traffic is generated based on the Erlang

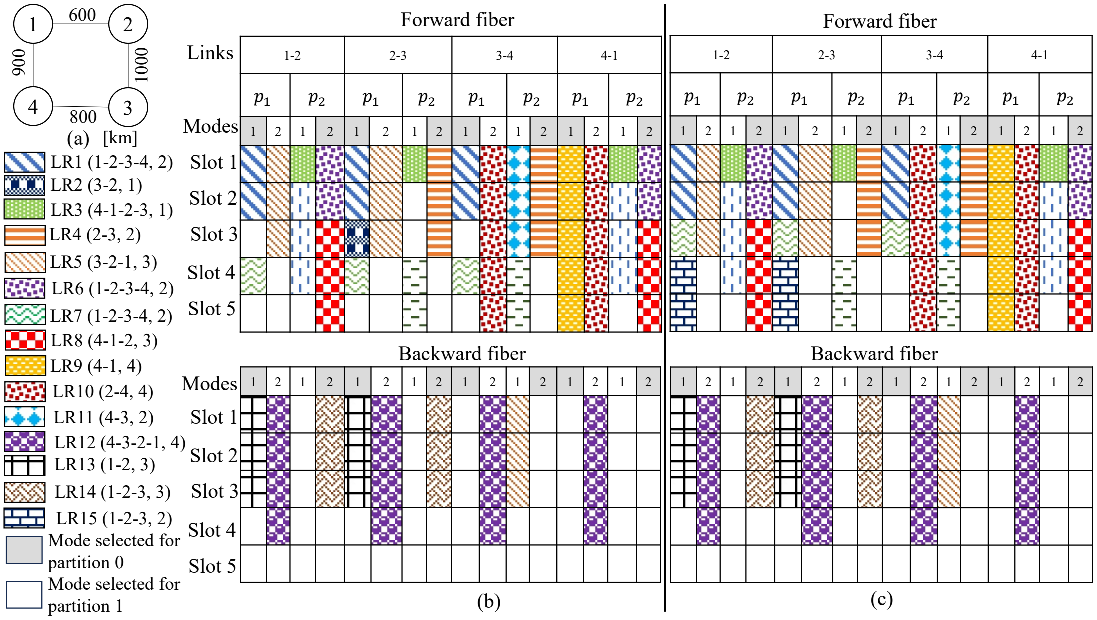


Fig. 2: (a) 4-node network, (b) spectrum allocation with 14 established requests before defragmentation, and (c) spectrum allocation after defragmentation, where LR15 is established through retuning following the termination of LR2.

model, defined by $\rho = \lambda \times H$, where the average holding time and inter-arrival rate of lightpath requests are denoted by H and λ, respectively. The holding time and inter-arrival time of lightpath requests are generated using an exponential distribution.

Lightpath demands are uniformly selected from 50, 100, 150, 200, 250, 300, 350, 400 Gbps. Six modulation formats are considered: PM-64-QAM, PM-32-QAM, PM-16-QAM, PM-8-QAM, PM-QPSK, and PM-BPSK, with supported transmission reaches ranging from 150 km to 6300 km [19]. The transmission reach model is used to determine the number of required slots [20]. Each spatial mode has a 4 THz spectrum (i.e., 320 slots). Parameters used in auxiliary graph construction follow prior studies [4]. The optimization subproblem (Section III-A) is solved using IBM ILOG CPLEX. All experiments are conducted on a Linux-based HPE ProLiant ML350 server equipped with Dual Intel Xeon Bronze 3106 processors (1.7 GHz) and 192 GB RAM.

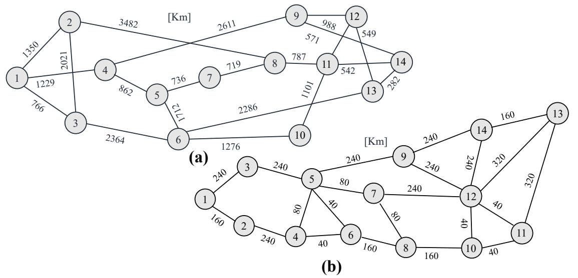


Fig. 3: Considered topologies: (a) NSF network [18] and (b) Japanese network [4].

For performance evaluation, we consider two benchmark approaches: counter-propagation-based resource allocation without defragmentation, named BPRIA [4], and priority-based co-propagation resource allocation without defragmentation, named PCMSA [1].

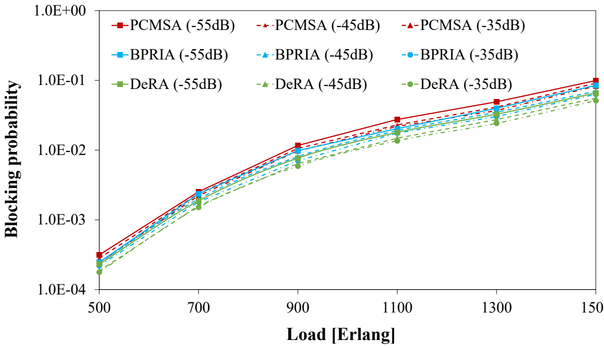


Fig. 4: Blocking probability with respect to traffic load for the NSF network.

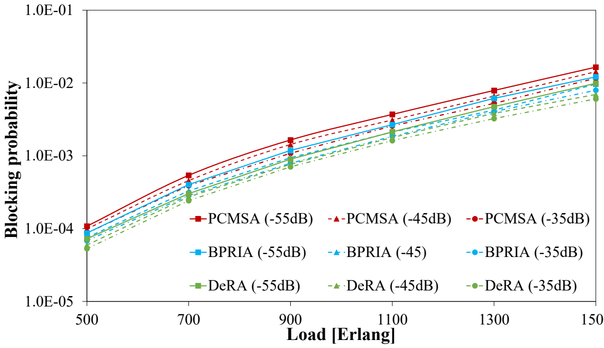


Fig. 5: Blocking probability with respect to traffic load for Japanese network.

Figures 4 and 5 illustrate blocking probability with traffic load for the NSF and Japanese network topologies, respectively. The comparison includes three approaches: DeRA, BPRIA, and PCMSA, each evaluated under auxiliary-threshold values of -25 dB, -35 dB, and -45 dB. Among these, the co-propagation-based PCMSA approach exhibits the highest blocking probability across all threshold values, as it employs unidirectional links and restricts the reuse of spectrum slots in adjacent cores and modes to minimize inter-core and inter-mode XT. The BPRIA method achieves lower blocking probability than PCMSA, while the DeRA scheme consistently provides the best performance. This improvement arises from its defragmentation-aware retuning mechanism, which efficiently reclaims fragmented spectrum and enhances slot continuity.

Furthermore, blocking probability increases for all schemes as the auxiliary-threshold value decreases, since a lower threshold limits the number of crosstalk-avoided resources. Conversely, higher thresholds allow more adjoint vertices to be formed in the auxiliary graph, leading to improved spectrum utilization and reduced blocking probability.

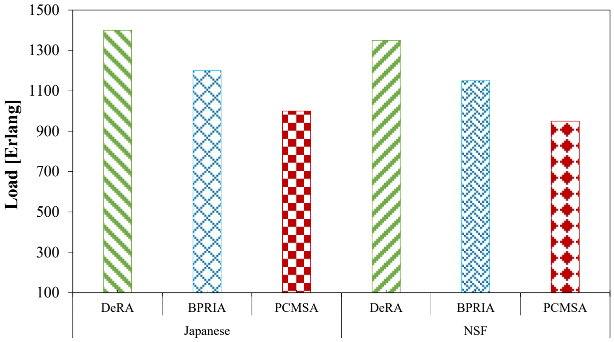


Fig. 6: Traffic admissibility in [Erlang] using different approaches for the Japanese and NSF networks under 1% blocking of requests.

Traffic admissibility is calculated under a 1% blocking constraint. As shown in Fig. 6, DeRA increases the admissible load by 40% and 32% compared to BPRIA and PCMSA in the Japanese and NSF networks, respectively. These improvements arise from topology-dependent factors such as node connectivity and path length. Networks with higher connectivity and fewer hops exhibit lower resource consumption per connection, resulting in a higher admissible load.

V. Conclusion

This paper proposed DeRA, a defragmentation-aware resource allocation scheme for spectrally-spatially elastic optical networks (SS-EONs) that effectively integrates counter-propagation and spectrum management. By partitioning the core-mode space using a bipartite graph optimization and applying reactive defragmentation to reorganize spectrum resources, DeRA simultaneously mitigates inter-core and inter-mode crosstalk while reducing spectrum fragmentation. Simulation results confirmed that DeRA significantly improves network performance, achieving lower blocking probability and higher spectral efficiency compared to BPRIA. We observed that DeRA accommodates 32 to 40% more admissible traffic than BPRIA under 1% blocking of requests.

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