RESILIENT AND FRAGMENTATION-AWARE MULTICAST ROUTING IN DYNAMIC DATA CENTER-ORIENTED SDM-EONs

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Abstract

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The rise of cloud services and data centers impose new challenges on optical networks, particularly in terms of capacity, resilience, and spectral efficiency. Spatial multiplexed elastic optical networks (SDM-EONs) represent a promising solution, although they face issues of spectral fragmentation, inter-core crosstalk, and fault tolerance. In this context, we propose DC-F-MRSA, a multicast extension of the DC-F-RSCA algorithm, designed to dynamically manage multicast traffic demands from data centers. This approach combines optimized core classification, a link and center fault protection strategy, and a core selection mechanism minimizing fragmentation and crosstalk. Experimental results on COST239 and NSFNET topologies show significant performance in terms of blocking rate, fragmentation, and fault robustness.

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Introduction: -

The continuous evolution of digital technologies, driven by the rise of cloud computing, data-intensive online services, and decentralized processing architectures, imposes increasing requirements on optical networks in terms of capacity, flexibility, and reliability.

To adapt to the variability of traffic demands, elastic optical networks (EONs) have been introduced. These enable fine-grained and dynamic allocation of spectral resources, leveraging flexible subcarrier slicing (frequency slots) [5]. However, in a dynamic environment, the random creation and deletion of connections induce the formation of spectral fragments, i.e., discontinuous blocks of unusable slots. This phenomenon leads to underutilization of the overall spectrum and increases the blocking rate of requests, limiting the overall efficiency of the optical network [9], [10].

To overcome these limitations, SDM-EONs (Space Division Multiplexing Elastic Optical Networks) architectures have been proposed. They exploit spatial multiplexing via multi-core fibers, each core being able to support an independent optical channel. This allows to significantly increase the capacity without multiplying the physical fibers [11]. However, this approach introduces new physical challenges, notably inter-core crosstalk, a phenomenon of electromagnetic interference between neighboring cores when signals of similar power coexist [12], [13]. Poor management of this phenomenon can significantly degrade the quality of service.

In data center-aware architectures (DC-aware), complexity increases further. The RSCA (Routing, Spectrum and Core Allocation) problem becomes multidimensional: it is no longer just a matter of ensuring continuity and spectral contiguity, but also of respecting crosstalk thresholds and guaranteeing resilience to failures (link or access failures to data centers). Multipath protection mechanisms or redundant replication then become necessary to ensure service continuity [1].

The existing literature mainly deals with unicast cases, where a single source communicates with a single destination [6], [10]. These approaches mostly address fragmentation or crosstalk, but in isolation and in environments that do not take into account the spatial dimension or dynamic constraints. Work on multicast traffic—in which a source simultaneously sends a stream to multiple destinations—remains rare, particularly in the context of SDM-EONs [7], [8].

Yet, multicast represents a strategic communication model in many modern applications: video streaming, data synchronization, distributed service updates, etc. Its implementation in SDM-EONs raises several combined challenges:

- he management of shared branches in broadcast trees;
- The requirement for consistent spectrum allocation across multiple simultaneous links;
- the joint minimization of fragmentation and crosstalk in a dynamic context;
- And fault tolerance, essential in critical environments.

To date, no solution in the literature addresses these issues in a unified manner within a single approach. To address this need, we propose, in this work, DC-F-MRSA, a resilient and fragmentation-aware multicast routing heuristic specifically adapted to dynamic SDM-EONs. The originality of our approach lies in:

- A dynamic classification of cores based on the level of crosstalk;
- A multipath protection model enabling rapid reconfiguration in the event of a failure;
- A global cost function that simultaneously integrates spectral fragmentation and crosstalk;
- And an optimized allocation strategy for shared branches of multicast trees

Our proposal is a direct extension of the DC-F-RSCA algorithm developed by Chandra et al. [1], initially designed for unicast traffic. It fills a clearly identified scientific gap by offering a complete, realistic solution compatible with the current needs of next-generation optical networks.

The remainder of this paper is structured as follows. Section 2 presents the related work, followed by contributions and hypotheses in Section 3. Section 4 formalizes the adopted network model, including the representation of multicast requests and allocation constraints. Section 5 describes in detail the proposed DC-F-MRSA heuristic, while Section 6 discusses the numerical results obtained from simulations. Finally, Section 7 concludes the paper and suggests perspectives for future work.

Related Work

Efficient routing and resource allocation (RSCA) management in elastic optical networks (EONs), particularly in dynamic contexts, has been the subject of extensive research. However, the majority of proposed solutions target unicast traffic and neglect the specificities of dynamic multicast traffic, even less so in SDM-EONs environments with multicore fibers. This section presents the main existing works, emphasizing their contributions and limitations with respect to our problem.

Work on Unicast Traffic and Fragmentation

Chandra et al. [1] proposed the DC-F-RSCA algorithm, combining core classification, multipath protection, and fragmentation management in data center-oriented SDM-EONs. Although their approach is resilient and fragmentation-aware, it only applies to unicast traffic and does not address the issue of shared paths in the case of multicast.

Other work, such as Walkowiak et al. [6], has studied path protection in EONs, while Castro et al. [10] highlighted the benefits of fragmentation-aware routing to reduce blocking rates. These contributions are important but remain limited to single-core topologies and do not address the physical constraints of SDM-EONs such as inter-core crosstalk.

Multicast in Conventional EONs

The approach of Yu et al. (2020) [8] is one of the first to propose fragmentation-aware multipath algorithms in SDM-EONs. However, their solutions are designed primarily for dynamic unicast environments and do not explicitly address the multicast issue, where resource management becomes more complex with distribution trees. Furthermore, they do not integrate adaptive mechanisms to simultaneously address crosstalk and network resilience.

Garrich et al. [7], in his work on optimized multicast trees, provides an effective cost minimization strategy. However, he does not take into account the dynamics of SDM-EONs (crosstalk, fragmentation, multi-cores) or data center-specific failures. The lack of fine-grained management of the physical and logical constraints of these networks makes their approach less applicable in cloud or mission-critical traffic scenarios.

Foundations of SDM-EONs and Physical Issues

From an architectural perspective, the work of Jinno et al. [5] and Richardson et al. [11] laid the foundations for elastic optical networks and spatial multiplexing (SDM). These advances have made it possible to multiply capacity by using multiple cores per fiber. However, Bocoi et al. [12] and Koshiba et al. [13] have shown that this architecture creates a new problem: inter-core crosstalk, which can deteriorate signal quality if streams are allocated to adjacent cores.

Despite these findings, very few RSCA models integrate these physical constraints into operational algorithms adapted to dynamic multicast traffic.

Limitations of Existing Approaches

The literature review shows that:

1) The majority of approaches are focused on unicast, limiting their applicability to collective flows.
2) The few studies on multicast neglect fragmentation and inter-core crosstalk.
3) Existing models do not integrate explicit protection against link or data center failures.
4) No identified work proposes synchronized allocation on shared branches of a multicast tree, a fundamental need.

Positioning of Our Approach

To address these shortcomings, we introduce DC-F-MRSA, a comprehensive heuristic dedicated to multicast traffic in dynamic SDM-EONs. It combines:

- optimized multicast tree construction;
- shared spectral allocation taking fragmentation and crosstalk into account;
- and multipath and DC-aware protection. Our model also introduces a multicast-aware cost function, evaluating each allocation choice on shared segments. This is a novel

contribution that addresses the combined challenges of scalability, robustness, and spectral performance in SDM-EONs.

Problem Statement

In spatially multiplexed elastic optical networks (SDM-EONs), supporting dynamic multicast traffic raises several complex challenges. Unlike unicast traffic, which connects a single source to a single destination, multicast involves the simultaneous distribution of an identical stream from a source to multiple destinations. To reduce spectrum consumption, multicast routing relies on the construction of a shared broadcast tree, where some links and spectral resources are reused between multiple paths. However, this structure introduces critical constraints that become more complex in a dynamic and multi-core environment.

Constraints on Shared Links in Multicast Trees

When dynamically routing multicast requests, some links in the tree are shared by multiple branches. As illustrated in Figure 1 below, these links must receive identical spectrum allocation for all branches that traverse them. This imposes strict spectral continuity and contiguity constraints on shared segments. However, in a dynamic environment, previous connections leave spectral fragments that significantly complicate the allocation of new continuous blocks. This phenomenon leads to artificial resource unavailability, even if the overall capacity is sufficient, increasing the blocking rate.

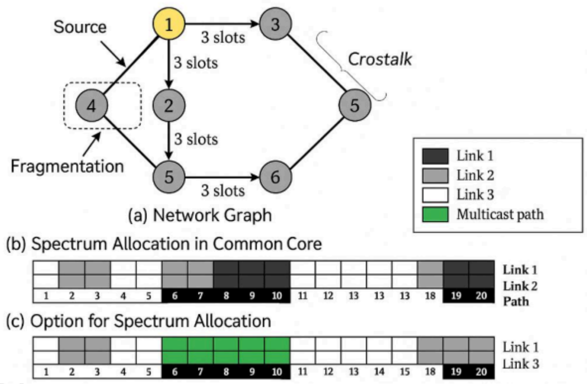

Figure-1: Illustration of the multicast routing problem in SDM-EONs

Part (a): Topology with 6 nodes and 2 multicast requests sharing some links.
Part (b): Spectral fragmentation on shared links.
Part (c): Effect of inter-core crosstalk on core allocation.

Spectral Fragmentation and Coordination

Part (b) of Figure 1 illustrates this phenomenon: although several links have free slots, it becomes difficult to find a common contiguous block across all shared segments. This mismatch between availabilities often prevents valid or efficient allocation. As network load increases, fragmentation reduces spectrum reusability, causing resource underutilization.

Inter-Core Crosstalk in SDM Networks

In SDM-EONs, each fiber contains multiple optical cores. Since these cores are physically adjacent, simultaneous signal transmission on neighboring cores can generate inter-core crosstalk, compromising signal quality. As shown in part (c) of Figure 1, if spectrum allocation is performed on adjacent cores for shared branches, crosstalk may exceed the allowed threshold, leading to degradation or rejection of the allocation.

Crosstalk-aware routing therefore becomes essential. However, traditional heuristics:

1) often ignore inter-core crosstalk;
2) or manage it independently of fragmentation;
3) and very rarely in a dynamic multicast context.

Problem Summary

The three constraints highlighted in Figure 1 can be summarized as follows:

1) Fragmentation on shared segments complicates spectrum allocation,
2) Inter-core crosstalk affects transmission quality,
3) Multicast requires strict synchronization of resources (cores + slots) on shared links.

Identified Gaps

To date, no algorithm offers a unified solution to:

1) dynamically manage multicast requests;
2) while minimizing fragmentation;
3) actively controlling crosstalk;
4) and ensuring fault resilience in SDM-EONs.

This justifies the development of our DC-F-MRSA heuristic, which integrates:

1) synchronized spectrum allocation on shared segments;
2) core selection sensitive to fragmentation and crosstalk;
3) and a multipath protection mechanism for fault tolerance;

Contribution and Hypotheses

SDM-EON Network Model

We model the spatially multiplexed elastic optical network as a directed graph:

$G = (V, E, C);$

where:

• V is the set of nodes (data centers or optical switches),
• E is the set of physical links,
• C is the number of optical cores available per fiber.

Each link is subdivided into spectral slots following a flexible OFDM grid, typically 6.25 or 12.5 GHz, in accordance with the ITU-T volume 2_Issue 1_paper-3 standards.

Multicast traffic Model

A multicast traffic query is defined as:

$R=(s,D,B,q)$

• s: source node,
• D={d1,d2,…,dn}a set of destinations,
• B: equired bandwidth (in number of FSs),
• q∈[0,1]: redundancy ratio for protection.

Each query requires the construction of a multicast tree, in which shared branches (common segments between paths) require strict coordination of spectrum allocation.

Allocation Constraints

The algorithm must respect the four fundamental constraints of RSA in EONs:
1. Spectral continuity: the same slots are allocated on all links in a path.
2. Contiguity: allocated slots must be adjacent.
3. Non-overlap: no slot reuse within the same fiber.
4. Inter-core crosstalk: induced crosstalk must not exceed a threshold XT_{th}

In SDM-EONs, the choice of the optical core strongly influences transmission quality due to spatial proximity. For this reason, the PAR method favors non-adjacent cores to minimize crosstalks.

Multicast-aware cost function

On the shared links of the multicast tree, we introduce a combined cost function:

$$F_{multi} = \sum_{e \in share} \left(\frac{\Delta_e + (\Gamma_e - \gamma_e)}{\phi_e} + CR(e)\right) \qquad \textit{(Eq. 1)}$$

where:
• Δe: number of fragments on the linke;
• Γe: total number of FS allocated;
• γe: slots actually used contiguously;
• Φe: slots still available;
• CR(e): crosstalk level measured on the allocated core;

This formulation takes and adapts the fragmentation formula proposed by DC-F-RSCA to incorporate the crosstalk specific to shared multicast.

Optimization Objective

The DC-F-MRSA heuristic aims to:
• Reduce the fragmentation rate (FR),
• Maintain an acceptable crosstalk level (CR),
• Guarantee service continuity even in the event of a failure.

It is based on adaptive core selection (SEQ or PAR) and an improved First-Fit spectrum allocation strategy for common segments.

5. Proposed Method: DC-F-MRSA

This section describes the mathematical, topological, and functional models underlying the DC-F-MRSA heuristic, designed for resilient multicast routing in data center-oriented SDM-EONs. The model integrates network physical characteristics, traffic dynamics, protection requirements, and a multi-criteria optimization mechanism based on fragmentation and crosstalk.

SDM-EON Network Model

The optical network is modeled using a directed graph:
G=(V,E,C);
where:
• denotes the set of nodes (data centers or optical switches),
• *E* is the set of bidirectional links between nodes,
• *C* represents the number of optical cores available per fiber.

Each link is divided into spectral slots (FS) according to a standardized OFDM grid, typically 6.25 or 12.5 GHz. The effective capacity of a link depends on both the number of available cores and the modulation format used.

Multicast Traffic Model

Dynamic traffic is composed of multicast requests denoted:

R=(s,D,B,q)

• *s*: source node,

• *D*={d1, d2,…,dn}a set of destinations,

• *B:* equired bandwidth (in number of FS),

• q∈ [0,1]: redundancy ratio for protection.

Each query requires the construction of a multicast tree, in which shared branches (common segments between paths) require strict coordination of spectrum allocation.

Protection Model

Protection against single-edge failures is based on a multipath mechanism, where B traffic is distributed over two or three disjoint paths according to the following formulas:

- Two paths:

$$b = B.q \ , \ b_{\ 2} = B - b_1 (Eq.2)$$

- Three paths:

$$b_{\ 1} = b_{\ 2} = \frac{B.q}{2}, \ b_{\ 3} = B - (b_{\ 1} + b_{\ 2}) \qquad (Eq.3)$$

In the event of a failure on a primary link, traffic is immediately rerouted to an alternative path without interruption of service.

Protection against single-DC failure is provided by an extension of the DC-P scheme [16], ensuring that each non-DC node is connected to at least two active data centers. A dynamic label system is used to balance the load between the different DCs.

Core Classification Model

To reduce fragmentation in spectral allocations, the model is based on core classification inspired by OPT-SBMC-RSCA [17]. Each fiber is divided into regions of increasing size according to the rule:

Region size of the i^e $core = 2^{(i-1)}$ FS, $i \in \{1, \ldots, C-1\}$The first core is said to be common, capable of hosting allocations of all sizes. This structuring allows for granular placement for bandwidth demands of varying sizes, while limiting the occurrence of fragments and the use of excessive guard bands.

Adaptive Modulation Model

The algorithm uses an adaptive modulation format selection model based on path distance. The formats adopted are:

Table1: modulation format

Modulation	Range (km	Capacity (Gbps)
BPSK	9600	12.5
QPSK	4800	25
8QAM	2400	37.5

16QAM	1200	50

Table 1presents, the number of slots required for a request is calculated by: $f_p = \left\lceil \frac{b_p}{m} \right\rceil (Eq. 4)$
where b_p is the requested bit rate on the p path, and m is the capacity of the selected modulation.

Overall Optimization Objective

The DC-F-MRSA heuristic aims to simultaneously minimize:
- The fragmentation rate (FR),
- The inter-core crosstalk (CR),
- And the blocking rate (BBR).

It relies on:
- Adaptive core selection via SEQ (minimizing fragmentation) and PAR (reducing crosstalk) strategies,
- A multi-criteria cost function to guide each allocation,
- And redundant traffic distribution, ensuring resilience and stability in critical multicast environments.

Proposed Heuristic: DC-F-MRSA

This section describes the DC-F-MRSA algorithm, a heuristic designed for dynamic multicast routing management, while ensuring resilience, minimizing spectral fragmentation, and reducing inter-core crosstalk in data center-oriented SDM-EONs. The approach is based on a multi-phase logic, each targeting a key constraint of the multicast-aware RSCA problem.

General Description of the Algorithm

The DC-F-MRSA heuristic operates according to the following steps:
1) Generation of the optimized multicast tree from the source to all destinations;
2) Selection of edge-disjoint paths for protection;
3) Selection of optical cores according to the SEQ or PAR strategies;
4) Evaluation of the overall cost function on shared segments;
5) Allocation of spectral slots according to physical constraints (continuity, contiguity, crosstalk, guard band);
6) Dynamic protection mechanism (DC and link) activated in case of failure.

Figure 1.

Algorithm 1 – DC-F-MRSA: A Resilient and Fragmentation-Aware Multicast Routing Heuristic

Input:

G(V, E, C) : SDM-EON network graph with nodes V, links E, and C cores per fiber
R(s, D, B, q) : Multicast request (source s, destinations D, bandwidth B, protection ratio q)

Output:

Routed and allocated multicast tree T, or Failure

1. Initialize the multicast tree T ← ∅
2. For each destination d ∈ D:
   a. Compute k edge-disjoint shortest paths between s and d
   b. Select best paths based on spectral cost criteria

3. Merge all paths to form an approximate multicast tree T
4. Apply DC-P mechanism to select two redundant data centers for fault tolerance
5. For each link $e \in T$:
    a. Evaluate all available core allocations ($c \in C$)
    b. Compute:
        - Local fragmentation Fe(e)
        - Crosstalk CR(e)
    c. Apply core selection:
        - SEQ mode: prioritize minimal fragmentation
        - PAR mode: prioritize minimal crosstalk
    d. Select optimal core c* using the multicast-aware cost function:
        $F\_multi(e) = (\Delta e + (\Gamma e - \gamma e)) / \Phi e + CR(e)$
6. Allocate spectrum slots using enhanced First-Fit strategy with constraints:
    - Contiguity
    - Continuity
    - Non-overlap
    - Crosstalk ≤ XT_th
7. If allocation succeeds for all links:
    a. Apply multipath protection (2 or 3 edge-disjoint backup paths)
    b. Return routed and allocated tree T
8. Else:
    Return Failure

Multicast Tree Construction

From a query *R = (s, D, B, q)*, an approximate multicast tree is constructed by merging the edge-disjoint paths between sss and each di∈Dd_i \in Ddi∈D, minimizing the total length of the tree. The algorithm uses a modified version of Bhandari's algorithm to extract multiple disjoint paths while maximizing shared segments.

Optical Core Selection

Two strategies are used:

• SEQ (Sequential): selection of contiguous cores to maximize spectral compactness and minimize fragmentation;

• PAR (Parallel): selection of non-adjacent cores to reduce inter-core crosstalk (CR), respecting the threshold XTth . The core is selected to minimize the cost function defined in Section 4.5. Shared segments are favored for joint allocation, thus conserving spectrum resources.

Spectrum Allocation

Slot allocation is performed using an improved First-Fit strategy, which ensures:

• Slot continuity across the entire source-destination path,
• Contiguity: slots must be adjacent,
• Absence of conflict (no overlap between concurrent flows),
• The presence of guard bands between simultaneous allocations,
• And compliance with the maximum crosstalk level.

How the Protection Mechanism Works

- Link Protection (Multipath):

For each flow, up to three edge-disjoint paths can be established. In the event of a link failure, the corresponding share of traffic is immediately rerouted via alternative paths according to the following distribution:

- $b_1 = b_2 = \frac{B.q}{2}$, $b_3 = B - (b_1 + b_2)$

Data Center Protection (DC-P):
Each non-DC node is connected to two active DCs. A dynamic labeling system balances the load on the data centers: the DC with the lowest label is prioritized to handle the request.

Algorithmic Complexity
The overall complexity of the heuristic is dominated by:
- The construction of disjoint multicast trees;
- The combined evaluation of fragmentation and crosstalk on shared segments;
- The verification of spectral constraints (continuity, contiguity, XT). The asymptotic complexity can be estimated as follows:

$$O(|D| \cdot |v| \cdot |E| \cdot |C| \cdot \theta) \qquad (Eq.5)$$

where:
- $|D|$est le nombre de destinations,
- $|V|$ le nombre de liens,
- $|C|$ le nombre de cœurs par fibre,
- θ la capacité maximale en FS par cœur.

It should be noted that the complexity of DC-F-MRSA exceeds that of DC-F-RSCA [1], due to the simultaneous management of multiple destinations, the construction of broadcast trees, and the combined evaluation of fragmentation and crosstalk on shared segments. However, this algorithmic overhead remains manageable, and is justified by the functional richness of the multicast model considered.

Numerical Analysis
The numerical results of DC-F-MRSA are analyzed in this section using various network metrics. Dynamic multicast traffic follows a Poisson distribution, with an exponentially distributed holding time. The algorithm's performance is evaluated based on three indicators: bandwidth blocking rate (BBR), inter-core crosstalk rate (CR), and spectral fragmentation rate (FR).
Simulations were conducted on two standard topologies: COST239 (11 nodes, 26 links) and NSFNET (14 nodes, 21 links). Each link has 12 optical cores containing 320 spectral slots, and traffic demands vary between 50 Gbps and 500 Gbps, with a protection ratio q ∈ [0.5, 1.0]. The analysis is based on 200 queries, repeated 25 times with a 95% confidence interval. 6.1 Comparative study between DC-F-MRSA-SEQ and DC-F-MRSA-PAR

Variation du BBR selon la charge

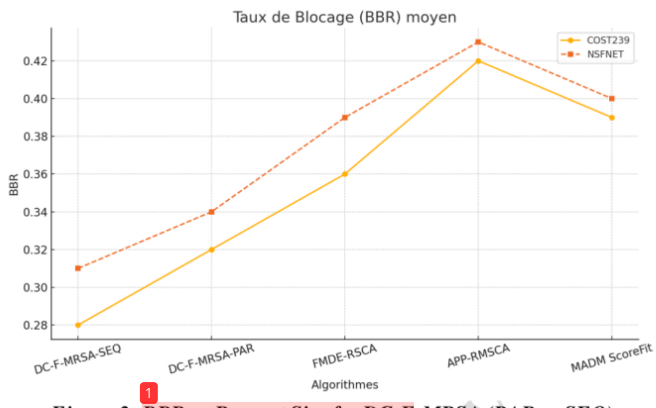

Figure-2: BBR vs Request Size for DC-F-MRSA (PAR vs SEQ)

As illustrated in Figure 2,the BBR increases with load, regardless of the topology. DC-F-MRSA-SEQ minimizes blocking through more compact spectrum utilization. COST239 has an overall lower BBR than NSFNET, due to its higher node degree.

CR Variation with Load

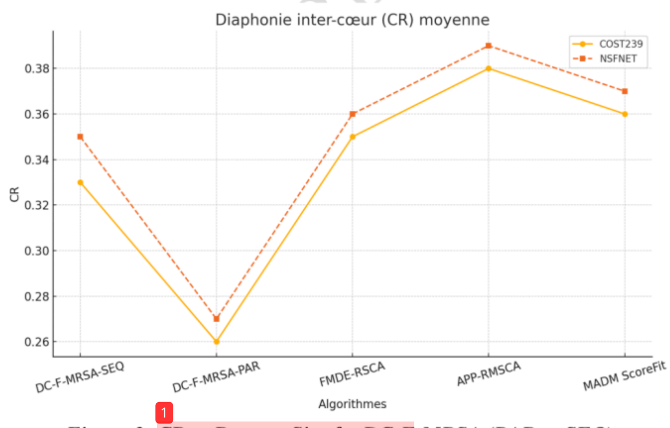

Figure-3: CR vs Request Size for DC-F-MRSA (PAR vs SEQ)

DC-F-MRSA-PAR significantly reduces crosstalk by choosing non-adjacent cores(see figure 3). The CR is higher on COST239 because shorter routes generate higher inter-core traffic density(see figure 3).

FR Variation with Load

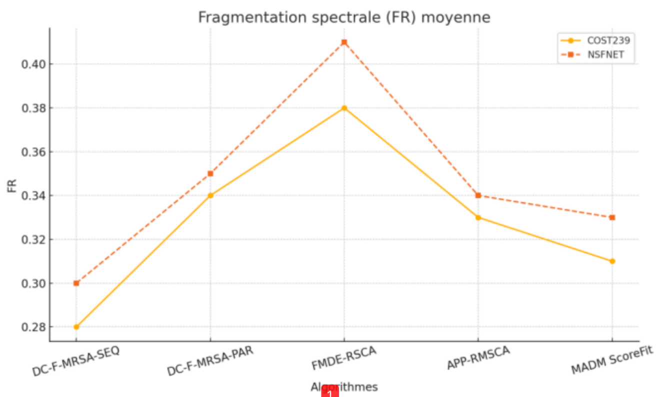

Figure-4: FR vs Request Size for DC-F-MRSA (PAR vs SEQ)

DC-F-MRSA-SEQ maintains lower fragmentation thanks to a sequential strategy and adaptive core classificationas shown inFigure 4. Traffic growth naturally increases fragmentation in both topologies.

Comparative Study of DC-F-MRSA with State-of-the-Art Heuristics

The performance of DC-F-MRSA is compared with three existing heuristics: MADM Score Fit, APP-RMSCA, and FMDE-RSCA. Only the SEQ strategy is used here to ensure the best spectral efficiency.

Comparison of BBR

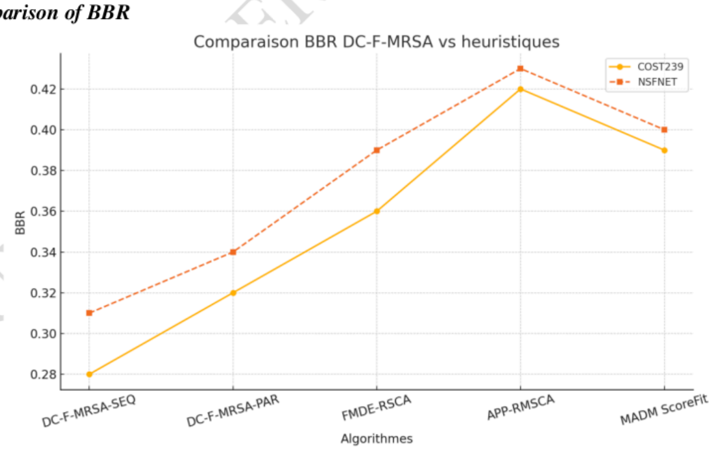

Figure-5: BBR Comparison: DC-F-MRSA vs Heuristics

DC-F-MRSA-SEQ has a lower BBR than FMDE-RSCA, due to better synchronization on shared segments asshownFigure 5. MADM and APP-RMSCA have a competitive BBR but do not incorporate resilience.

CR Comparison

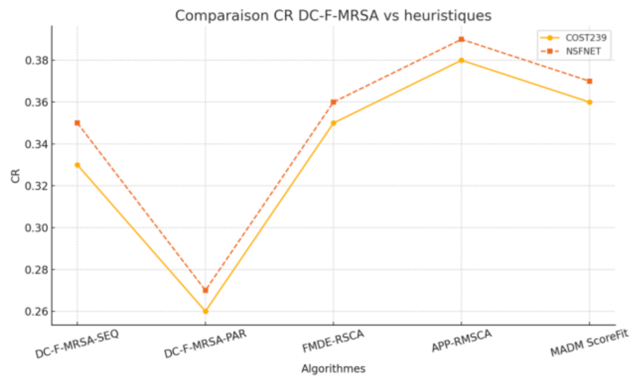

Figure-6 : DC-F-MRSA vs Heuristics

CR is better controlled by DC-F-MRSA (especially PAR), thanks to the explicit consideration of crosstalk in the algorithm. FMDE-RSCA and APP-RMSCA completely ignore crosstalk, resulting in a higher CR (see fugure 6).

Comparison of FR

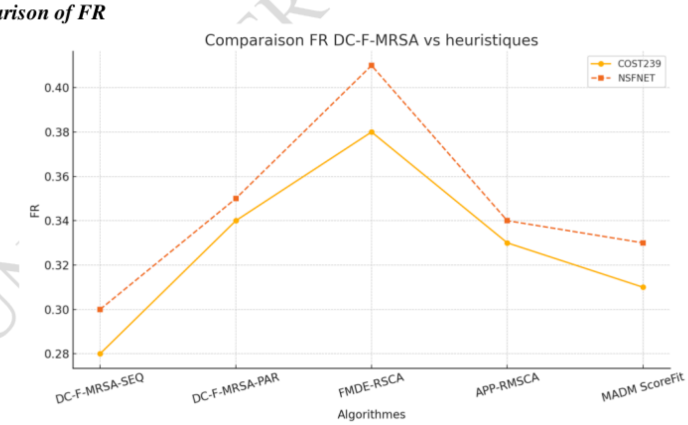

Figure-7: FR Comparison: DC-F-MRSA vs Heuristics

As illustrated in Figure 7, DC-F-MRSA-SEQ offers lower spectral fragmentation than FMDE-RSCA and APP-RMSCA.

Core classification allows for better slot allocation, even under heavy load.

Conclusion and Future Work

This paper presented **DC-F-MRSA**, a novel heuristic dedicated to resilient and fragmentation-aware multicast routing in dynamic SDM-EONs. Building upon the DC-F-RSCA model originally developed for unicast traffic, our approach integrates multicast tree construction, adaptive core selection strategies (SEQ and PAR), and a cost function that jointly considers spectral fragmentation and inter-core crosstalk.

Through extensive simulations on two well-known topologies (COST239 and NSFNET), we demonstrated that DC-F-MRSA achieves a significant reduction in bandwidth blocking ratio (BBR), crosstalk ratio (CR), and fragmentation ratio (FR) compared to state-of-the-art heuristics such as FMDE-RSCA, MADM Score Fit, and APP-RMSCA. The results confirm the superiority of our method, particularly in dynamic scenarios with multicast demands, where synchronized resource allocation on shared links is essential.

Furthermore, the use of SEQ and PAR strategies allows a trade-off between fragmentation minimization and crosstalk mitigation, enabling network operators to adapt the algorithm according to performance needs.

In future work, we plan to extend DC-F-MRSA with:

- **Machine learning models** for traffic prediction and adaptive path selection;
- **Real-time traffic scenarios** for experimental validation in programmable optical testbeds;
- **Energy consumption metrics** to evaluate the sustainability of the proposed method.

Ultimately, DC-F-MRSA opens a promising pathway for the integration of scalable, robust, and resource-efficient multicast services in next-generation optical infrastructures.

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