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Dynamic routing, spectrum, and modulation-format allocation in mixed-grid optical networks

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Traffic in optical backbone networks is evolving rapidly in terms of type, volume, and dynamicity following the rapid growth of cloud-based services, ongoing adoption of 5G communications, and explosion of the Internet of Things (IoT). The elastic optical network (EON), by adopting a flexible grid, can provide the required capacity and flexibility to handle these rapid changes. However, operators rarely perform greenfield deployments, so to limit upfront investment, a gradual migration from fixed-grid to flexible-grid switching equipment is preferable. For gradual migration, switching nodes can be upgraded (starting from bottleneck network links) while keeping the rest of the traditional fixed-grid network operational. We refer to the coexistence of fixed-grid and flex-grid optical equipment as a "mixed-grid" network. Traditional algorithms for dynamic resource assignment in EONs will not effectively be applicable in a mixed-grid network due to interoperability issues among fixed- and flex-grid nodes. In this study, we propose a new algorithm, called Mixed-grid-aware Dynamic Resource Allocation, to solve the route, spectrum, and modulation-format allocation problem in a mixed-grid network while considering interoperability constraints. Our numerical results (on representative network topologies) show that the proposed method achieves 50% less blocking (for 50% offered load) compared to the traditional approach.

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1. INTRODUCTION

A massive increase in global IP traffic volume [with a compound annual growth rate (CAGR) of 26%] has been forecast in the Cisco global visual networking index (VNI) for 2017–2022 [1], where the CAGR is dominated primarily by video traffic (82% of IP traffic), while most of this traffic is generated from wireless and mobile devices (71% of IP traffic). Existing wavelength-division multiplexing (WDM) backbone networks based on a fixed-grid subdivision of the spectrum need to evolve to carry such heterogeneous, high-volume, and high-bit-rate traffic, while ensuring high resource utilization. The elastic optical network (EON), thanks to its flexible assignment of spectrum resources and its adaptive transponder technologies, offers an effective solution to serve this evolving traffic. However, given the large amount of currently operational fixed-grid networks, in some cases (e.g., when the network is single-vendor, or in future scenarios where equipment disaggregation is supported), migration towards a flex-grid EON can happen through a gradual process. In fact, gradual (or brownfield) migration towards a flex-grid infrastructure provides an opportunity to optimize the cost of deployment, to minimize the wastage of previously deployed WDM equipment, and to prevent disruption in regular network operations.

Various studies show how to migrate from a fixed- to flex-grid network [2–4]. They suggest to localize bottleneck nodes/links in the network as an initial point to start upgrading them to operate on a flex-grid. During this upgrade, some existing switching nodes operating with fixed spectrum slots of 50 GHz will be substituted with optical architectures capable of managing variable-width optical channels consisting of multiples of basic frequency slots at 12.5 or 25 GHz.

These flex-grid nodes are typically equipped with wavelength-selective switches (WSSs) [5,6] and symbol-rate adaptable transponders [7] to offer flexibility. This will result in lightpaths operating at different bit rates (e.g., 10, 40, 100, 200, 400 Gb/s) that can be allocated over different channel widths using different modulation formats, e.g., binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and quadrature amplitude modulatoin (8QAM, 16QAM, and 32QAM). Also, larger bit rates (e.g., 400 Gb/s, 1 Tb/s) can be achieved by using superchannels.

Although these technologies are available now, they are not widely deployed yet. Gradual migration strategies have been proposed [2–4] using higher bit rates and advanced modulation formats only for specific connections by upgrading nodes based on some node-merit metric such as (1) upgrading nodes that generate/carry the most traffic first, (2) upgrading nodes that generate/carry high traffic variation first, (3) upgrading nodes that generate/carry the most low/high-bandwidth traffic first, or (4) upgrading nodes with the highest nodal degree first.

During this migration process, fixed-grid and flex-grid technologies would need to interoperate, introducing new planning and operational challenges for network operators. Most prior works either have studied migration strategies or proposed resource allocation in an EON. Few works address the operational challenges in a mixed-grid environment, e.g., migration-aware routing (MAR) [8], static routing and spectrum allocation (RSA) techniques [9], dynamic routing (shortest path) and spectrum allocation (first-fit) in a pre- and postmigration scenario [3], modulation-format and spectrum allocation in an EON [10], etc. Some recent works propose solutions such as split-spectrum or subband virtual concatenation (VCAT) [11,12], where traffic demand is split and transmitted via multiple optical subchannels for better flexibility. However, these works either use standard RSA techniques in a mixed-grid network or propose solutions with higher complexity and cost. In our work, a dynamic route, spectrum, and modulation-format allocation (RSMA) is proposed, which exploits diverse modulation formats and provides higher spectral efficiency while maintaining complexity close to standard techniques.

Clearly, a mixed-grid network raises new challenges that require modifications in traditional network operations. Our work focuses on resource allocation while ensuring seamless adaptation to network heterogeneity. We propose an algorithm called Mixed-grid-aware Dynamic Resource Allocation (MDRA), which includes a spectrum-efficient dynamic route allocation (SEDRA) algorithm, reusable spectrum allocation first (RSAF), and a distance-adaptive modulation-format allocation. Performance evaluation is done with respect to bandwidth blocking over two large topologies with various traffic profiles. Our results depict 50% reduction in the bandwidth blocking ratio (BBR) for practical load values while using our solution compared to state-of-the-art ones.

The rest of this study is organized as follows. In Section 2, related works are reviewed. In Section 3, lightpath provisioning challenges in a mixed-grid network are introduced and represented through examples. Section 4 formally states the RSMA problem in a mixed-grid network and describes a possible strategy to solve the problem based on existing approaches for the EON. Section 5 contains our proposed algorithm. Section 6 introduces the performance evaluation metrics that have been considered as well as numerical results with explanations. Section 7 concludes the study.

2. RELATED WORKS

Most prior studies propose RSMA solutions on a fully flexible EON without addressing any intermediate migration stages. Reference [8] discusses brownfield migration from a fixed-grid to a flexible grid in optical networks. The authors proposed a MAR algorithm for resource provisioning. Their proposed algorithm first calculates the probability of each node in the network to be upgraded to a flex-grid node. Based on these probabilities, it routes lightpaths to avoid any interruption due to any future migration. Reference [9] focuses on RSA in a mixed-grid network considering a postmigration scenario. The authors proposed integer linear programming formulations along with static heuristic algorithms to minimize spectrum utilization.

Reference [3] presented a comparison on various migration strategies. It adopted a traditional k-shortest path and first-fit technique for route and spectrum allocation, respectively, to compare the performance of these migration strategies. Reference [13] evaluated the impact on network capacity of deploying a flex-grid solution over a network that is partially loaded with fixed-grid channels. The authors proposed several migration strategies from fixed-grid to flex-grid networks.

Considering modulation-format adaptability in the EON, Ref. [10] proposed distance-adaptive spectrum allocation, where minimum spectral resource is adaptively allocated to make better use of the resource. The study considered both modulation formats and optical filter width to determine the necessary spectral resources to be allocated to an optical path. It adopted a traditional fixed-alternate routing and a first-fit spectrum assignment algorithm to provision lightpaths. Most studies on modulation-format adaptability of the flex-grid are limited to pure flex-grid networks (not the mixed-grid scenario).

In Refs. [11,12], the authors introduce the concept of subband VCAT in a mixed-grid optical network, improving spectrum utilization. They propose a subband VCAT to enable lightpath connections to be established between different types of nodes and to allow the traffic demand to be split and transmitted via multiple optical subchannels for better flexibility and greater spectral efficiency. They proposed mixed integer linear program models and a heuristic algorithm based on spectrum window planes for RSA optimization. Although VCAT can help with better spectrum utilization, the guard band required between neighboring split subchannels may waste fiber spectra and also increase the number of transponders and signal regenerators used.

In the preliminary version of this work [14], we proposed a novel routing algorithm, called SEDRA, in a mixed-grid network. It provisions routes for dynamic, heterogeneous traffic, ensuring maximum spectrum utilization and minimum blocking in a mixed-grid network. We evaluated the BBR for both uniform and Poisson distribution of traffic arrivals.

In this current work, various additional contributions are included. First, we propose a new resource-allocation algorithm MDRA, which includes SEDRA, as well as RSAF and distance-adaptive modulation-format allocation, the latter being the most significant addition. For this algorithm, we evaluated various baseline routing, spectrum allocation, and modulation-format allocation strategies. Second, we evaluated the performance of MDRA on a denser network (the 24 node USnet topology). Third, we investigated the effect of different numbers of flex-grid nodes in the network. Fourth, we made detailed comparison of MDRA with baseline strategies by investigating metrics such as average number of hops per path and percentage of requests blocked in this study.

3. CHALLENGES DUE TO MIGRATION STRATEGIES

Migration strategy depends on network topology, traffic distribution, locality of traffic, network bottlenecks, traffic profiles, etc. It also depends on the type (fixed/flex) of neighboring nodes. If a fixed-grid node with a flex-grid neighbor node is being upgraded, a high-rate superchannel can be set up between them. Also, a higher modulation format can be adopted on the route. Therefore, studies [2,3] have recommended migration through creating multiple independently growing flex-grid islands. A flex-grid island is defined as a subset of network nodes with flexible-grid technology. Multiple such islands are required to grow, based on the traffic distribution in the network. Figure 1 shows an example of flex-grid islands. Here, we consider a U.S.-wide backbone network where flex-grid islands are being formed with nodes located in the east and west coastal areas, where the traffic is assumed to be higher than in the rest of the network.

The next two subsections explain (through an example) the spectrum assignment in a mixed-grid network with and without distance-adaptive modulation formats, respectively. A fixed modulation format of dual-polarization (DP)-QPSK is assumed for the non-distance-adaptive case, irrespective of the distance between the source and destination. Figures 2 and 3 demonstrate different cases of spectrum assignment in mixed-grid scenarios. We assume that fixed-grid and flex-grid have a basic frequency slice of 50 GHz and 12.5 GHz, respectively. Note that wavelength continuity and contiguity constraints must be respected at node B.

A. Spectrum Assignment in a Mixed-Grid Network without Distance-Adaptive Modulation

Figure 2 shows part of a mixed-grid network where lightpaths traverse both flex-grid and fixed-grid links. Spectrum occupation of signals with various bit rates are reported in Table 1 [3]. There are three nodes and two links in this example.

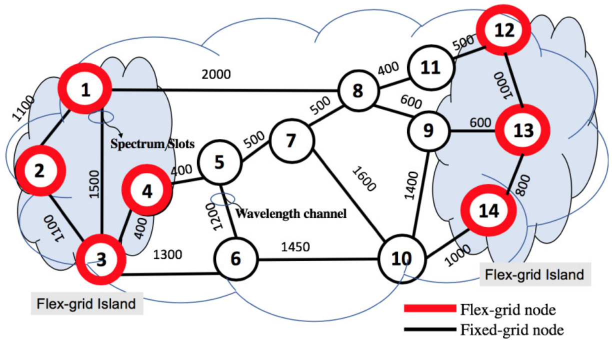

Fig. 1. Coexisting fixed/flex-grid in the 14-node NSFnet topology.

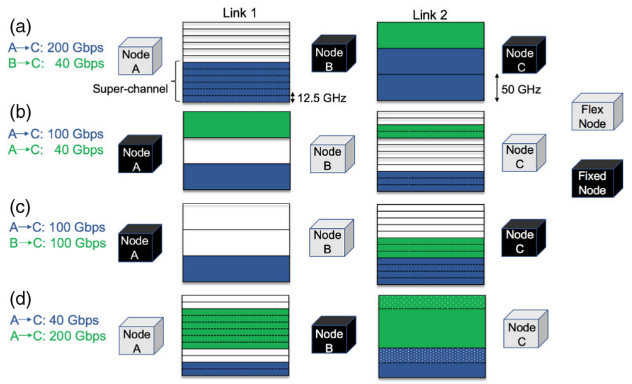

Fig. 2. Spectrum assignment in different mixed-grid scenarios: (a) connection requests A → C: 200 Gbps, B → C: 40 Gbps; (b) connection requests A → C: 100 Gbps, A → C: 40 Gbps; (c) connection requests A → C: 100 Gbps, B → C: 100 Gbps; and (d) connection requests A → C: 40 Gbps, A → C: 200 Gbps.

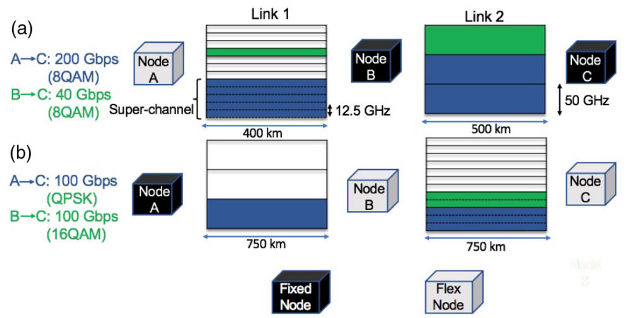

Fig. 3. Spectrum assignment in different mixed-grid scenarios using different modulation formats: (a) connection requests A → C: 200 Gbps (8QAM), B → C: 40 Gbps (8QAM) and (b) connection requests A → C: 100 Gbps (QPSK), B → C: 100 Gbps (16QAM).

We assume that a link has 150 GHz capacity, where fixed-grid and flex-grid links would have 3 wavelength channels and 12 frequency slots, respectively. In Fig. 2(a), a lightpath request of 200 Gbps, originating at a flex-grid node (node A), terminates into a fixed-grid island of two fixed-grid nodes (nodes B and C). According to Table 1, link 1 needs six slots (75 GHz), whereas link 2, being in a fixed-grid island, needs two lightpaths of 50 GHz (total 100 GHz) to allocate the same 200 Gbps connection request (hence, an O/E/O conversion is required at node B). In link 1, the flex-grid uses a superchannel; on the contrary, in link 2, the limitation of the fixed-grid to

Table 1. Spectrum Occupation for Various Bit Rates

	Fixed-Grid		Flex-Grid	
Traffic Demand (Gb/s)	Bandwidth (GHz)	# Wavelengths	Bandwidth Gap (GHz)	# Slots
40	50	1	25	2
100	50	1	37.5	3
200	100	2	75	6
400	200	4	150	12

allocate higher bit rates in a single channel is observed. The second connection request of 40 Gbps, which originates from node B, stays in a fixed-grid island and is assigned a 50 GHz slot. For the 200 Gbps traffic request at each link, 25 GHz (2×12.5 GHz) of the spectrum is saved in the flex-grid link compared to the fixed-grid link.

On the contrary, in Fig. 2(b), lightpaths originating from a fixed-grid node are ending in a flex-grid island. 100 Gbps connection requests from node A to C occupied 50 GHz in link 1 and 37.5 GHz in link 2. Now, a 40 Gbps connection request is assigned between nodes A to C, with 50 GHz and 25 GHz occupation in link 1 and 2, respectively. Here, for the same connection requests, the flex-grid link occupies 37.5 GHz less spectrum in total than the fixed-grid link.

Figures 2(c) and 2(d) represent scenarios where lightpaths originate and terminate at the same type of islands but traverse through a different one. Lightpaths should maintain transparency while traversing through different islands. In Fig. 2(c), a 100 Gbps connection request is set up between nodes A to C. This request originates and terminates into a fixed-grid island, traversing through a flex-grid island. To maintain transparency, a lightpath starts with 50 GHz on link 1 and comes out from the flex-grid island with the same 50 GHz (four slots) signal. On the contrary, the second connection request of 100 Gbps originating from node B occupies only (three slots) 37.5 GHz instead. Similarly, in Fig. 2(d), a 40 Gbps connection request occupies two slots (25 GHz) in link 1 but takes up a 50 GHz channel in link 2, where the signal occupies only 25 GHz in the channel, while the rest of the spectrum is not used (blue with white dots). The same happens with the 200 Gbps connection request.

B. Spectrum Assignment in a Mixed-Grid Network with Distance-Adaptive Modulation

Another key technical advancement towards EONs is the introduction of dynamically adjustable modulation formats. Advanced modulation formats offer a higher bit rate and spectral efficiency (bits/s/Hz), at the cost of a lower optical reach. Distance adaptivity [15,16] is achieved using modulation-adaptive transmitters [7,17]. Combination of distance-adaptive coherent transceivers with flex-grid links enables even higher spectrum utilization. Figure 3 shows spectrum assignment in mixed-grid scenarios assuming the spectrum occupancies for various bit rates as reported in Tables 1 and 2 [12,18–20]. Transmission performance (e.g., reach, operating bandwidth, optical signal-to-noise ratio) of any optical lightpath depends on various factors (fiber, load, and system characteristics), which requires accurate physical-layer models. In our study, we employ a simplification (commonly used in network-layer studies) consisting of setting a maximum optical reach value for a given set of possible bit rates. These values are reported in Table 2 and are taken from studies that considered the Gaussian noise model [21]. Figure 3 has the same settings as Fig. 2 with additional capability of assigning a spectrum based on different modulation formats that satisfy distance between the source and destination.

In Fig. 3(a), a lightpath request of 200 Gbps originates at a flex-grid node (node A) and terminates into a fixed-grid island of two fixed-grid nodes (nodes B and C) having a source-destination distance of 900 km. We observed in Fig. 2 that link 1 needs six slots (75 GHz) whereas link 2 being in a fixed-grid island would need two lightpaths of 50 GHz (100 GHz) to allocate this request using DP-QPSK. However, with inclusion of distance-adaptive properties in node A (a flex-grid node), it can use a higher modulation format such as 8QAM, which still satisfies the 900 km reach requirement (see Table 2). The spectrum occupation in link 1 is 62.5 GHz, whereas link 2 being in a fixed-grid island would need two lightpaths of 50 GHz (100 GHz) as before. However, the overall spectrum occupation ($62.5 + 100 = 162.5$ GHz, compared to 175 GHz) is reduced in this distance-adaptive approach using higher modulation. Similarly, a second connection request of 40 Gbps requires only one slot (12.5 GHz) in link 1 but one wavelength channel (50 GHz) in link 2 using the modulation format of 8QAM. With a non-distance-adaptive route and spectrum allocation technique, link 1 would need two slots (25 GHz) to allocate this 40 Gbps request using DP-QPSK.

Now in Fig. 3(b), a lightpath originating from a fixed-grid node is ending in a flex-grid island. A 100 Gbps connection request from node A to C occupies 50 GHz in link 1 and 37.5 GHz in link 2 using DP-QPSK from fixed-grid node 1. If node 1 were also a flex-grid node, for a distance of 1500 km, it could use 8QAM, which needs only 25 GHz in each link. A second lightpath request of 100 Gbps from nodes B to C occupies only two slots (25 GHz) from link 2 (flex-grid) using 16QAM.

Standard strategies for resource assignment in EONs are not effective for mixed-grid networks. Therefore, we propose a "mixed-grid-aware" algorithm for a novel solution to the dynamic RSMA problem in a mixed-grid network.

Table 2. Distance and Spectrum Occupation for Various Bit Rates in Flex-Grid

Traffic Demand (Gb/s)	Modulation Format	Operating Bandwidth (GHz)	Distance (km)	# Slots
40	BPSK	50	6000	4
	QPSK	25	3000	2
	8QAM	25	1000	1
100	BPSK	75	4500	6
	QPSK	50	3500	4
	QPSK	37.5	3000	3
	8QAM	25	2500	2
	16QAM	25	1500	2
200	BPSK	100	2500	8
	QPSK	75	1500	6
	8QAM	62.5	1000	5
	16QAM	43.75	700	4
	32QAM	37.5	500	3
400	BPSK	200	2000	16
	QPSK	150	1000	12
	8QAM	100	800	8
	16QAM	75	600	6
	32QAM	56.25	200	5

4. PROBLEM STATEMENT AND SOLUTION STRATEGIES

A. Problem Statement

In this study, we address the RSMA problem in a mixed-grid network, where dynamic traffic requests with heterogeneous bit rate and various traffic profiles are being provisioned. We propose a spectrally efficient route selection technique ensuring maximum reusability of resources, and distance-adaptive modulation formats are assigned to achieve higher spectrum utilization and lower BBR compared to benchmark techniques.

The dynamic "on-demand" traffic provisioning problem can be defined as follows: given a network topology (with a set of fixed/flex-grid nodes and links with limited spectrum resources) and incoming traffic requests, find optimal route, spectrum, and modulation format to satisfy the requests while minimizing the BBR.

B. Solution Strategies

Several strategies can be devised, resulting from the combination of different RSA policies, as shown below.

1. Routing Policies

Shortest-Path First (SPF): SPF [22,23] precomputes a single fixed route for each source-destination pair using a shortest-path algorithm, such as Dijkstra's algorithm [24]. When a connection request arrives in the network, it tries to establish a lightpath along the precomputed fixed route. It checks whether the desired slot is free on each link of the precomputed route or not. The request is blocked if one link of the precomputed route does not have the desired slot.

Most Slots First (MSF): This policy [25] keeps track of available slots at each link of a path. It precalculates *k*-shortest paths using *k*-SPF and arranges them in descending order based on their total available slots obtained from slot availability on their links. Finally, it selects the path with the most available slots. This policy avoids congestion and uniformly distributes the traffic load. In the process, it may take longer routes compared to the route along the shortest path.

Largest Slot-over-Hops First (LSoHF): This policy [25] keeps track of available slots at each link and path length, which is measured in terms of hop count (links). It precalculates the *k*-shortest paths and arranges them in descending order based on the ratio between total available slots and corresponding path length in hops of each path. Finally, it selects the path with the highest value of this ratio (available slots/hops). This policy takes care of the problem of MSF taking longer routes by taking into account path lengths. If a path is taking too many hops, it would automatically be eliminated from being the first to be selected.

Spectrum-Efficient Dynamic Route Allocation (SEDRA): SEDRA is the applied routing policy in this work. It finds the route that requires the least spectral allocation among the *k*-shortest routes. For example, in Fig. 4, let us consider a 100 Gb/s traffic demand from node 5 to node 1. The first three shortest paths in terms of hops are calculated and marked in three different traits shown with dotted, solid, and dashed

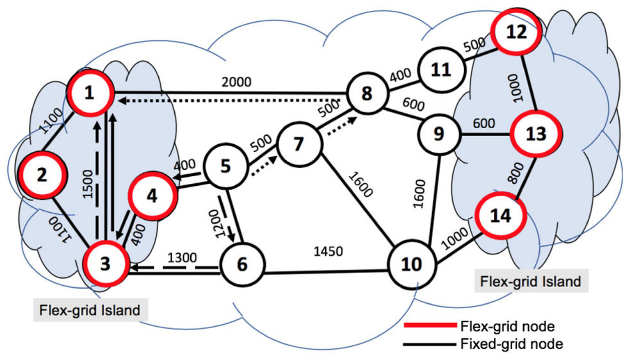

Fig. 4. Route, spectrum, and modulation-format allocation using SEDRA.

lines, respectively, in Fig. 4. According to Fig. 2 and Table 1, the spectrum requirement for these three paths (assuming DP-QPSK) can be calculated as follows:

- Path 1, 5-7-8-1 (three fixed-grid and one flex-grid nodes): $(50 * 3)$ GHz $= 150$ GHz.
- Path 2, 5-4-3-1 (one fixed-grid and three flex-grid nodes): $(50 + 37.5 * 2)$ GHz $= 125$ GHz.
- Path 3, 5-6-3-1 (two fixed-grid and two flex-grid nodes): $(50 * 2 + 37.5)$ GHz $= 137.5$ GHz.

Path 2 is the most spectrally efficient route for the request. Although all three paths have the same number of links, paths 1 and 3 will waste more spectrum. SPF routing may choose any of these paths as their hop count is the same. However, SEDRA chooses path 2, which has higher spectral efficiency.

2. Spectrum Allocation Strategies

First Fit (FF): This policy [26] tries to find the lower-most indexed slot in available spectrum slots. By choosing spectrum in this way, lightpaths are gathered into fewer spectrum slots, which helps to increase the contiguous-aligned available slots in the network [27].

Random Fit (RF): This policy [23] maintains a list of available spectrum slots. When a lightpath request arrives, it arbitrarily selects slots from available slots for lightpath provisioning. It continuously updates available spectrum slots in the process of lightpath allocation and de-allocation. By selecting spectrum slots in a random manner, a network operator tries to reduce the possibility of some specific slots being used too often [27]. Allocated spectrum slots are expected to be uniformly distributed over the entire spectrum.

RSAF: This policy maintains two separate lists of available slots: at-least-once-used slots and never-used slots. When a lightpath request arrives, this policy selects slots from the used slots first using the FF policy. If no slots are available in this list, it selects from the list of never-used slots using the FF policy. Choosing spectrum slots this way is an effort to enhance the reuse of spectrum in the network.

3. Modulation-Format Assignment Strategies

We consider two assumptions regarding modulation-format assignment: (i) fixed or non-distance-adaptive modulation-format assignment (which has been assumed to always be DP-QPSK)—in this case, k-shortest paths are calculated for minimizing the number of hops, as this is the most spectrally efficient choice—and (ii) distance-adaptive modulation-format assignment in which we incorporate the distances in km to calculate the shortest path. Modulation formats are selected depending on the distance needed to cover to reach the destination.

In Fig. 4, let us consider the same 100 Gb/s traffic demand from node 5 to node 1 as we did while explaining SEDRA. The shortest path is selected as 5-4-3-1 with a distance of 2300 km. According to Fig. 3 and Table 2, the spectrum requirement and modulation formats can be selected as follows:

- Non-distance-adaptive approach, 5-4-3-1 (one fixed-grid and three flex-grid nodes, QPSK, 3000 kms): $(50 + 37.5 * 2)$ GHz $= 125$ GHz.
- Distance-adaptive approach, 5-4-3-1 (one fixed-grid and three flex-grid nodes, 8QAM, 2500 kms): $(50 + 25 * 2)$ GHz $= 100$ GHz.

By using a distance-adaptive modulation format, we can use even fewer spectra to provision the same lightpath request.

5. PROPOSED ALGORITHM: MIXED-GRID-AWARE DYNAMIC RESOURCE ALLOCATION

In this section, we describe our proposed algorithm, MDRA, which is a combination of SEDRA and RSAF with modulation-format allocation. We show that this combination performs the best in the next section. Given parameters:

– $N(V, E)$: Network topology, with V set of nodes and E set of edges.
– V_{FI}: Set of fixed-grid nodes.
– V_{FL}: Set of flex-grid nodes, where $V = V_{\mathrm{FI}} \cup V_{\mathrm{FL}}$.
– $n_s(l)$: Start node of a link l, where $n_s(l) \in V$.
– $n_e(l)$: End node of a link l, where $n_e(l) \in V$.
– C_l: Capacity of link in GHz.
– W_{FI}: Frequency slice in fixed-grid links in GHz.
– W_{FL}: Frequency slice in flex-grid links in GHz.
– $\alpha_{s,d}$: Traffic request between nodes S and node D in Gbps.
– ϕ_v: Boolean value which defines if a node v is fixed(0)/flex-grid(1), where $v \in V$.
– ϕ_s: Boolean value which defines if a source node is fixed(0)/flex-grid(1), where $v \in V$.
– $\phi_{n_s(l)}$: Boolean value which defines if the start node of link l is fixed(0)/flex-grid(1).
– $\phi_{n_e(l)}$: Boolean value which defines if end node of link l is fixed(0)/flex-grid(1).
– $P_{s,d}$: Set of k shortest paths $p_{s,d}$ between source s and destination d, where $p_{s,d} \in P_{s,d}$.
– ψ_l^n: Boolean value which defines if link l has n contiguous available slots for a request.
– $\kappa_{s,d}$: Set of candidate paths with requested contiguous slot availability, where $\kappa_{s,d} \subseteq P_{s,d}$.

Algorithm 1. Mixed-grid aware Dynamic Resource Allocation (MDRA)

1: **Input:** $N(V, E)$, V_{FI}, V_{FL}, C_l, W_{FI}, W_{FL}, $p_{s,d}$, $\alpha_{s,d}$;
2: **Output:** Route, Spectrum, and Modulation Format;
3: **for each** connection request $(\alpha_{s,d})$ **do**
4: $P_{s,d} \leftarrow$ find set of k-shortest paths $\alpha_{s,d}$;
5: ▹ list of candidate paths with available spectrum
6: **for each** $p_{s,d}$ **in** $P_{s,d}$ **do**
7: **if** $(spectrum\_avail(p_{s,d}, \alpha_{s,d}) == True)$ **then**
8: $\kappa_{s,d} \leftarrow \kappa_{s,d} \cup p_{s,d}$;
9: **for each** $p_{s,d}$ **in** $\kappa_{s,d}$ **do**
10: $m \leftarrow modulation\_format(p_{s,d}, \alpha_{s,d})$;
11: $\gamma_T^p \leftarrow calculate\_spectrum(p_{s,d}, \alpha_{s,d}, m)$;
12: ▹ find path requiring least spectrum for $\alpha_{s,d}$
13: **if** γ_T^p is lowest **then**
14: $\gamma_{min}^p \leftarrow \gamma_T^p$;
15: $p_{s,d}^{best} \leftarrow p_{s,d}$;
16: $m^{best} \leftarrow m$;
17: Allocate lightpath on $p_{s,d}^{best}$ using modulation format m^{best} to achieve minimum spectrum allocation of γ_{min}^p.

– γ_l^p: Required spectrum on link l of $p_{s,d}$ for $\alpha_{s,d}$.
– γ_T^p: Total required spectrum slice over all links of $p_{s,d}$ for $\alpha_{s,d}$.
– γ_{min}^p: Lowest required spectrum over all links of $p_{s,d}$ for $\alpha_{s,d}$.
– n: Number of slots required in a fixed/flex-grid link for $\alpha_{s,d}$.
– n_o^l: List of available slots on link l which were used at least once.
– n_n^l: List of available slots on link l which were never used.
– $p_{s,d}^{\mathrm{best}}$: Path requiring lowest spectrum to allocate $\alpha_{s,d}$.
– m^{best}: Best modulation for given request and distance.
– p^l: Path length.
– p^{fixed}: Boolean value which denotes whether the path consists of all fixed-grid nodes.

In MDRA, a mixed-grid-aware spectrally efficient RSMA is applied for varying traffic requests (see Algorithm 1 for detailed pseudo-code). This algorithm is a combination of SEDRA, RSAF, and distance-adaptive modulation-format allocation. The algorithm finds k-shortest path $P_{s,d}$ for a given traffic request $\alpha_{s,d}$ (lines 1–4 in Algorithm 1). Next, it checks which of these paths has enough spectrum availability (lines 6–10 in Algorithm 1) for requested $\alpha_{s,d}$. Function *spectrum_avail( )* (Algorithm 2) calculates contiguous slot availability for each path using function *mixed_grid_spectrum( )* (Algorithm 3), and returns 'true' if slots are available on a path. Function *mixed_grid_spectrum( )* identifies the location of fixed and flex-grid nodes along the path and returns γ_l^p as required spectrum for $\alpha_{s,d}$. The paths that have the required contiguous slots are listed in a candidate path list (line 8 in Algorithm 1). Now, the modulation format (Algorithm 5) and corresponding spectrum allocation (Algorithm 4) for each of the candidate paths are calculated (lines 11–13 in Algorithm 1). The modulation format for corresponding path length p^l is calculated using Table 2. For SEDRA without a distance-adaptive modulation-format property, the modulation format is fixed to DP-QPSK.

Algorithm 2. **spectrum_avail( )**

Input: $p_{s,d}$, $\alpha_{s,d}$;
Output: Boolean, spectrum available or not;
$m \leftarrow modulation\_format(p_{s,d}, \alpha_{s,d})$;
for each link l **in** $p_{s,d}$ **do**
  $\gamma_l^p \leftarrow mixed\_grid\_spectrum(s, n_s(l), n_e(l), \alpha_{s,d}, m)$;
  Requested number of slots, $n \leftarrow \gamma_l^p / W_{FL}$;
    $\triangleright$ first find n contiguous slots on n_o^l slots else find in n_n^l of link l
  if $\psi_l^n == false$ **then**
    return $false$;
return $true$;

Algorithm 3. **mixed_grid_spectrum( )**

Input: s, $n_s(l)$, $n_e(l)$, $\alpha_{s,d}$, m;
Output: γ_l^p;
if $\phi_s == 0$ **then**
  if $\phi_{n_s(l)} == 0$ **then**
    $calculate\_spectrum(0, \alpha_{s,d}, m)$
      $\triangleright$ check node type: fixed/flex-grid;
  else if $(\phi_{n_s(l)} == 1$ & $\phi_{n_e(l)} == 0)$ **then**
    $calculate\_spectrum(0, \alpha_{s,d}, m)$;
  else if $(\phi_{n_s(l)} == 1$ & $\phi_{n_e(l)} == 1)$ **then**
    $calculate\_spectrum(1, \alpha_{s,d}, m)$;
else
  if $\phi_{n_s(l)} == 1$ **then**
    $calculate\_spectrum(1, \alpha_{s,d}, m)$;
  else if $(\phi_{n_s(l)} == 0$ & $\phi_{n_e(l)} == 1)$ **then**
    $calculate\_spectrum(0, \alpha_{s,d}, m)$;
  else if $(\phi_{n_s(l)} == 0$ & $\phi_{n_e(l)} == 0)$ **then**
    $calculate\_spectrum(0, \alpha_{s,d}, m)$;
return γ_l^p.

Algorithm 4. **calculate_spectrum( )**

Input: ϕ_v, $\alpha_{s,d}$, m;
Output: γ_T^p;
$\gamma_T^p \leftarrow 0$;
for each link l **in** $p_{s,d}$ **do**
  $\gamma_l^p \leftarrow$ find minimum required spectrum for $\alpha_{s,d}$ and modulation format m from Tables 1 and 2;
  $\gamma_T^p \leftarrow \gamma_T^p + \gamma_l^p$;
return γ_T^p;

Function *calculate_spectrum* (Algorithm 4) then calculates the minimum spectrum required, $\gamma_{\min}^p$ on path p for $\alpha_{s,d}$. The path that requires minimum spectrum $\gamma_{\min}^p$ is called the best path, $p_{s,d}^{\text{best}}$, and the modulation format used to achieve minimum spectrum allocation is denoted by m^{best} (lines 15–22 in Algorithm 1).

6. ILLUSTRATIVE NUMERICAL RESULTS

Results were obtained over two U.S. network topologies with variation in number of nodes and links. We first considered the 14-node NSFnet topology for analysis. We also considered the 24-node USnet backbone network topology to verify our findings for a larger network. Selection of fixed-grid and flex-grid nodes was predetermined in both. Half of the nodes were considered to be fixed-grid and another half to be flex-grid. Flex-grid nodes are located at east and west coastal areas. For the 14-node NSFnet network, the number of fixed-grid links = 14, and the number of flex-grid links = 6. For the 24-node USnet network, the number of fixed-grid links = 29, and the number of flex-grid links = 14. The capacity of each optical fiber link was assumed to be 5 THz. This leads to 100 wavelengths for a fixed-grid link with a spectrum width of 50 GHz and 400 frequency slots, each of 12.5 GHz, for a flex-grid link. For traffic demand, random pair-connection requests with a Poisson interarrival and an exponential holding time of mean 15 s are generated. Today, optical network traffic is of mostly semistatic or static in nature. However, traffic is evolving towards a more heterogeneous and application-oriented nature for which the dynamicity is expected to rise. Even today some use cases for dynamic traffic can be found, as science data exchanges over a network such as ESnet [28] or as dynamic ligthpath provisioning in response to important social events (Olympics, concerts, etc.). When we consider a dynamic scenario, we evaluate the absolute performance of our algorithm for this kind of future traffic. Moreover, dynamic traffic studies give an indication also of how to effectively allocate resources in the presence of new-arriving traffic requests (incremental traffic demands). To represent heterogeneous traffic, three traffic profiles (Table 3) are considered. Profile 1 mimics predominantly low-bandwidth traffic. In profile 2, 100 Gb/s traffic is predominant, representing moderate load. In profile 3, all traffic is 100 Gb/s or higher with a significant increase in 400 Gb/s, representing heavy load.

Algorithm 5. **modulation_format( )**

Input: $p_{s,d}$, $\alpha_{s,d}$;
Output: m;
$p^l \leftarrow$ find path length of path $p_{s,d}$;
$p^{fixed} \leftarrow$ find if $p_{s,d}$ has all fixed-grid nodes;
if $p_{fixed} == True$ **then**
  return DP-QPSK;
else
  return highest modulation format with reach p^l for $\alpha_{s,d}$ using Table 2.

Table 3. Traffic Profiles

Traffic Demand (Gb/s)	Profile 1	Profile 2	Profile 3
40	50%	20%	0%
100	30%	50%	40%
200	15%	20%	40%
400	5%	10%	20%

A. Performance Evaluation Metrics

Performance of the proposed algorithm is evaluated based on the blocked bandwidth and spectrum utilization with gradual increments of normalized offered traffic load. The following are the performance evaluation metrics considered to evaluate MDRA against other strategies.

BBR = rejected bandwidth ÷ total requested bandwidth.

Normalized offered load is calculated based on the amount of traffic arrival compared to the total spectrum capacity of the network. However, total network capacity varies with selection of different modulation formats. It is difficult to calculate network capacity based on each modulation format and make the comparison. Therefore, we assumed 100 Gbps and DP-QPSK to be our baseline standards for network capacity calculation.

Offered load = (connection arrival rate × average request size × average holding time × average path length) ÷ network capacity.

Network capacity = number of fixed-grid links × channel capacity (in GHz) × spectral efficiency of fixed-grid + number of flex-grid nodes × channel capacity in GHz × spectral efficiency of flex-grid, where

- Spectral efficiency of fixed-grid links = 100 ÷ 50 = 2 bits/s/Hz,
- Spectral efficiency of flex-grid links = 100 ÷ 37.5 = 2.6 bits/s/Hz.

The average hops traversed for each path and the percentage of request blocking in terms of individual traffic demands were also computed for in-depth analysis.

B. Simulation Results

For a route selection problem, the performance of the algorithm depends on the number of shortest paths, k. In the following graphs, k is chosen to be 10, as we have simulatively verified that no significant gain is achieved above $k = 10$. The graphs that are shown in this section correspond to the results on the NSFnet, with the exception of Fig. 11, which shows results from USnet.

Figure 5 plots the BBR of four routing techniques with spectrum allocation policy RSAF for increasing traffic load, using traffic profile 1. MDRA is a combination of SEDRA and RSAF. As MDRA allocates the least spectrum, it achieves the lowest blocking among all, confirming the intuition that, in a mixed-grid, MDRA can outperform existing strategies. For example, for 50% offered load, SPF (0.12) blocks 50% more bandwidth requests compared to MDRA (0.06). MSF has the worst BBR performance (0.28 for 50% offered load) of all four as it does not constrain spectrum usage.

Figure 6 compares the BBR of the three spectrum-allocation strategies, when applied with SEDRA. SEDRA with RSAF (MDRA) performs the best in terms of BBR as it promotes spectrum reusability, which helps to accommodate more requests. RF has the highest BBR, as it results in sparse spectrum allocation, causing fragmentation and lack of contiguous slots for new connections. FF has intermediate performance but is still worse than RSAF.

Figure 7 represents the average hop count taken by all four routing strategies. MDRA and SPF both allocate an average number of hops around 2.4 (for low loads, below 30%). The difference starts at 35% load (see Fig. 7). SPF experiences resource shortage and blocks the connection request from this point onwards. Most of the network spectrum becomes

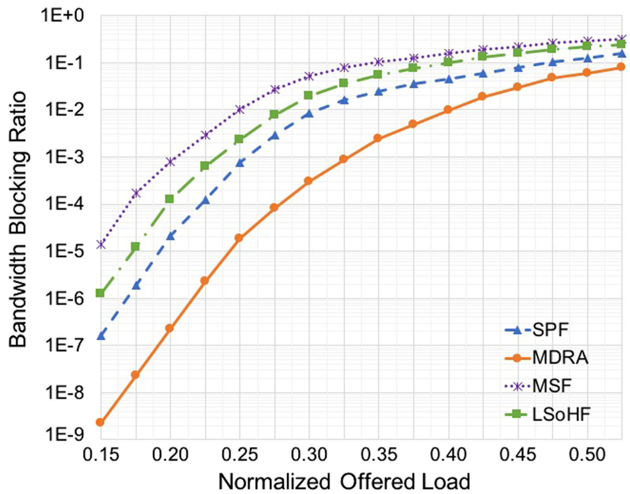

Fig. 5. Comparison of bandwidth blocking ratio (for NSFnet).

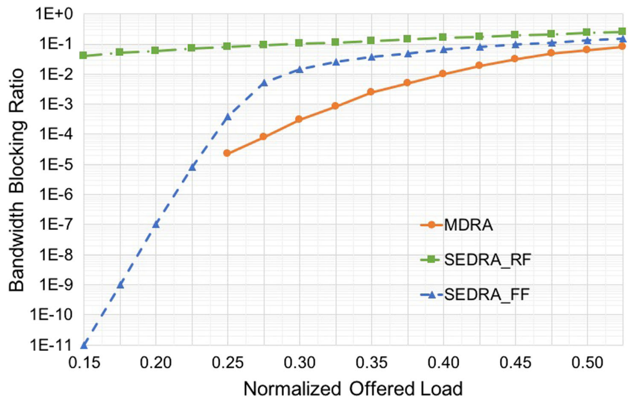

Fig. 6. Comparison of spectrum allocation strategies (for NSFnet).

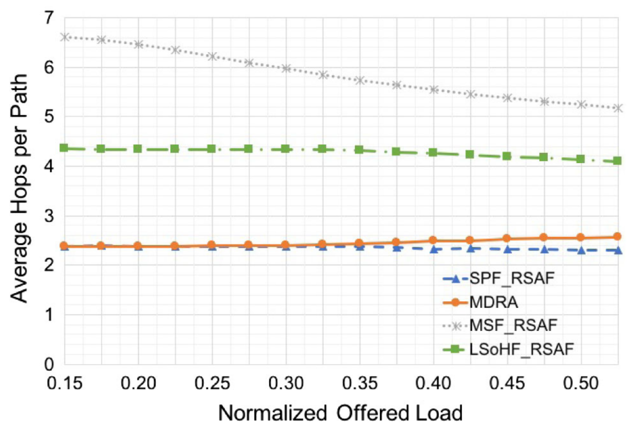

Fig. 7. Comparison of the average hop count among different routing strategies (for NSFnet).

exhausted now; therefore, the average number of hops per connection request gradually decreases (to 2.3 in SPF). MDRA with a comparatively lower blocking ratio takes longer routes (up to 2.56 average hop count) to allocate requests when

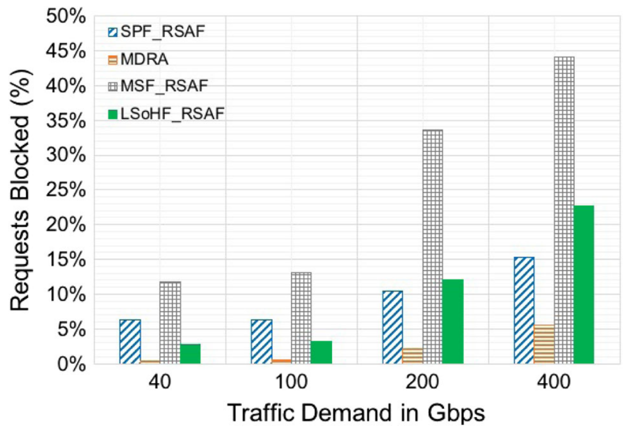

Fig. 8. Requests blocked from individual bit rates (for NSFnet).

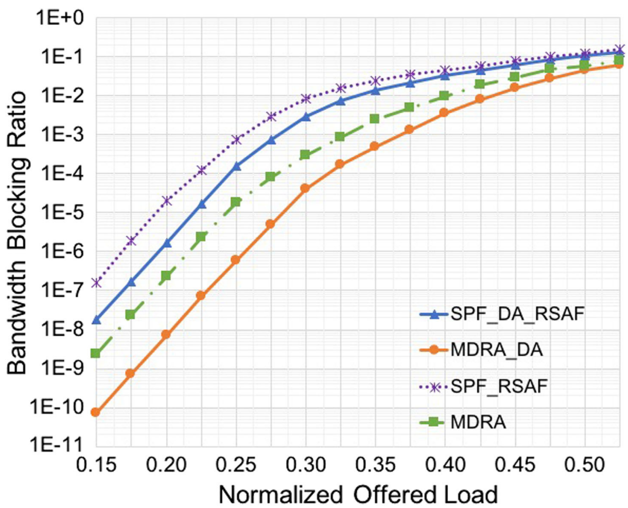

Fig. 9. Comparison of the BBR with and without distance-adaptive modulation (for NSFnet).

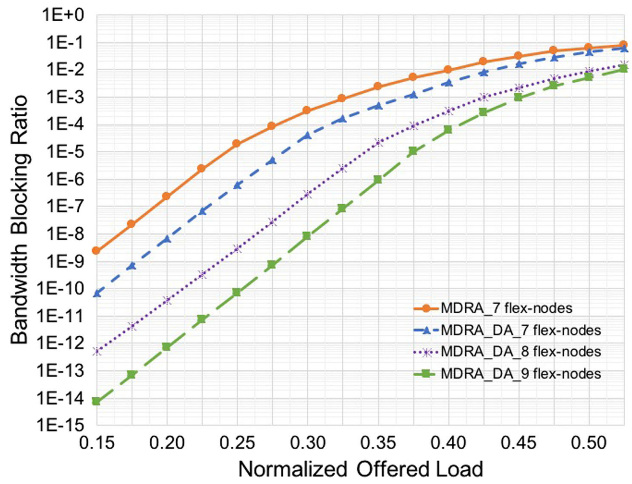

Fig. 10. Comparison of the BBR with varying flex-grid nodes (for NSFnet).

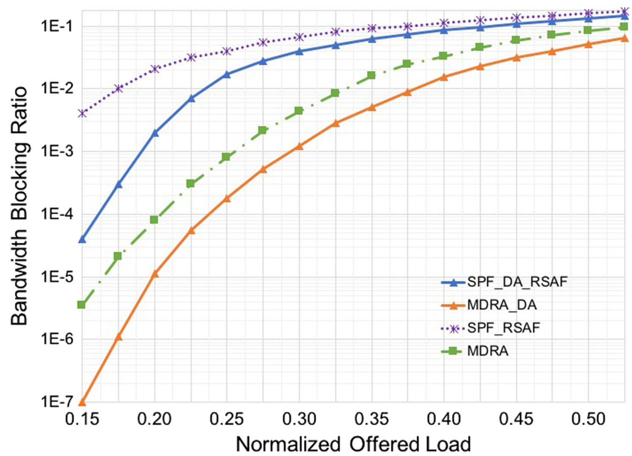

Fig. 11. Comparison of the BBR with and without the distance-adaptive modulation format (for USnet).

shorter paths are congested. As MSF does not minimize spectrum allocation, and only focuses on paths with the highest available spectrum, it takes longer paths (up to 6 hops) compared to all four strategies. LSoHF does balance between provisioning the shorter path with the highest availability. Therefore, the average hop count (up to 4.3 hops) is lower than MSF but not lower than SPF and MDRA. In summary, for 50% offered load, MDRA achieves a 50% lower BBR than SPF, with the cost of 11% increased hop count.

Figure 8 shows a breakdown of lightpath blocking for traffic demands with different bit rates. All routing strategies block the lowest number of 40 Gbps connections. As expected, blocking increases with increasing bit rate, but MDRA blocks fewer requests due to its mixed-grid-aware properties.

Figure 9 compares the BBR of MDRA and SPF with and without distance-adaptive modulation-format allocation (denoted with DA in the figure). Inclusion of the DA modulation format increases spectral efficiency, resulting in less blocking. It is worth noting that this decrement in BBR is more significant in MDRA than in SPF (e.g., for 50% load, improvement in BBR is 25% for MDRA and only 15% for SPF).

Figure 10 considers a migration scenario where the number of flex-grid nodes is increased gradually. Here, a comparison of the BBR is done by setting an increasing number of flex-grid nodes for MDRA and MDRA_DA. It is already shown that MDRA_DA has a lower BBR than the MDRA without DA modulation format. The number of flex-grid nodes also plays a role in the BBR performance of MDRA. As the number of flex-grid nodes grows, the capacity of a network to accommodate more connection requests also grows.

Figure 11 depicts the comparison of the BBR with and without the distance-adaptive modulation format in a 24-node USnet topology. Observations seen for the 14-node NSFnet are confirmed. SPF and MDRA both improve their BBR using DA modulation formats. However, MDRA_DA achieves 40% BBR reduction, whereas SPF_DA achieves 16% BBR reduction compared to the case without the DA modulation format (at 50% offered load). USnet topology, having a higher nodal degree, gives more route options to MDRA to achieve lower blocking.

7. CONCLUSION

Migration towards a flex-grid network is eminent to meet the ever-growing traffic demands. Network operations need to be adaptive to any changes during the process of this migration. RSMA in a mixed-grid network introduces new challenges for network orchestration. In this study, a mixed-grid-aware spectrum-efficient solution, called MDRA, is proposed for dynamic traffic. MDRA routes heterogeneous traffic with lower spectrum allocation. Distance adaptivity is obtained by dynamically adjusting modulation formats, achieving even higher spectrum efficiency. Illustrative results show up to 50% BBR reduction compared to baseline solutions. Also, 25% BBR reduction is achieved with DA modulation-format allocation compared to the non-DA approach. We also performed detailed analysis of impact from different traffic profiles, the number of flex-grid nodes, modulation formats, and network topology, to gain more insights on RSMA for mixed-grid networks.

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