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 Internet of Things (IoT). 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 co-existence of fixed-grid and flex-grid optical equipment as a "mixed-grid" network. Traditional algorithms for dynamic resource assignment in EON will not effectively be applicable in a mixed-grid network due to inter-operability issues among fixed and flex-grid nodes. In this study, we propose a new algorithm, called Mixed-grid-aware Dynamic Resource Allocation (MDRA), to solve the route, spectrum, and modulation-format allocation (RSMA) problem in a mixed-grid network while considering inter-operability constraints. Our numerical results (on representative network topologies) show that the proposed method achieves 41% less blocking (for 50% offered load) compared to traditional approach. The proposed method also can gain about 15% more spectrum utilization for same load.

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1. INTRODUCTION

Massive increase in Global IP traffic volume (with 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. 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 cost of deployment, minimizes wastage of previously-deployed WDM equipment, and prevents disruption in regular network operations.

Various studies show how to migrate from fixed to flex-grid network [2] [3] [4]. They suggest to localize bottleneck nodes/links in network as a initial point to start upgrading them to operate on flex-grid. During this upgrade, some existing switching nodes operating with fixed spectrum slots of 50 GHz will be substituted with optical architectures capable to manage 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., BPSK, QPSK, 8QAM, 16QAM, 32QAM, etc. Also, larger bit rates (e.g., 400 Gb/s, 1 Tb/s) can be achieved by using super-channels.

Although these technologies are available now, they are not widely deployed yet. Gradual migration strategies have been proposed [2] [3] [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) upgrade nodes that generate/carry most traffic first, (2) upgrade nodes that generate/carry high traffic variation first, (3) upgrade nodes that generate/carry most low/high-bandwidth traffic first, or (4) upgrade nodes with 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 a EON. Few works address the operational challenges in a mixed-grid environment, e.g., migration-aware routing [8], static routing and spectrum allocation techniques [9], dynamic routing (shortest path) and spectrum allocation (first-fit) in a pre- and post-migration scenario [3], modulation-format and spectrum allocation in EON [10], etc. Some recent works propose solutions such as split-spectrum or sub-band virtual concatenation [11] [12] where traffic demand is split and transmitted via multiple optical sub-channels for better flexibility. However, these works either use standard routing and spectrum allocation techniques in a mixed-grid network or propose solutions with higher complexity and cost. In our work, a dynamic 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 which require modifications in traditional network operations. Our work focuses on resource allocation while ensuring seamless adaptation to network heterogeneity. We propose an algorithm Mixed-grid-aware Dynamic Resource Allocation (MDRA) which includes 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 and spectrum utilization over two large topologies with various traffic profiles. Our results depict 41% reduction in bandwidth blocking ratio (BBR) and 15% gain in spectrum utilization 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 EON. Section 5 contains our proposed algorithm. Section 6 introduces the performance evaluation metrics which 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. Ref. [8] discusses brown-field migration from fixed grid to flexible grid in optical networks. The authors proposed a migration-aware routing (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. Ref. [9] focuses on routing and spectrum allocation (RSA) in a mixed-grid network considering post-migration scenario. The authors proposed ILP formulations along with static heuristic algorithms to minimize spectrum utilization.

Ref. [3] presented a comparison on various migration strategies. It adopted traditional k-shortest path and first-fit technique for route and spectrum allocation, respectively, to compare the performance of these migration strategies. Ref. [13] evaluated the impact on network capacity of deploying a flex-grid solution over a network which 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 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 flex-grid are limited to pure flex-grid networks (not mixed-grid scenario).

In [11] [12], authors introduce the concept of sub-band virtual concatenation (VCAT) in mixed-grid optical network, improving spectrum utilization. They propose sub-band VCAT to enable lightpath connections to be established between different types of nodes, and allow the traffic demand to be split and transmitted via multiple optical sub-channels for better flexibility and greater spectral efficiency. They proposed mixed integer linear program models and 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 sub-channels 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 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 (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 metrices such as Average Number of Hops per Path, Spectrum Utilization Ratio, 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 super-channel 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. Fig. 1 shows an example of flex-grid islands. Here, we consider a US-wide backbone network where flex-grid islands are being formed with nodes located in east and west coast areas, where the traffic is assumed to be higher than in the rest of the network.

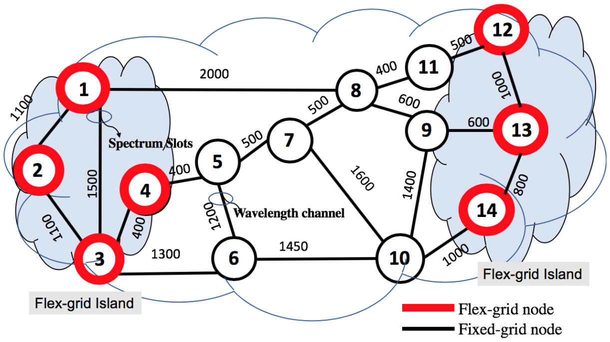

Fig. 1. Co-existing fixed/flex-grid in 14-node NSFNet topology.

The next two sections explain (through an example) spectrum assignment in a mixed-grid network with and without distance-adaptive modulation formats, respectively. A fixed modulation format of Dual Polarization Quadrature Phase Shift Keying (DP-QPSK) is assumed for non-distance-adaptive case, irrespective of the distance between source and destination. Figs. 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

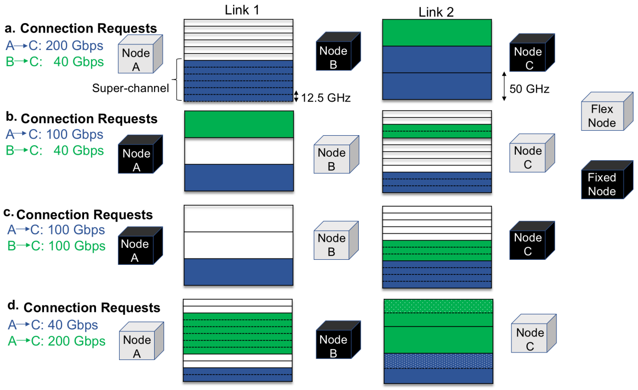

Fig. 2. Spectrum assignment in different mixed-grid scenarios.

Fig. 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].

Table 1. Spectrum occupation for various bit rates.

Traffic Demand (Gb/s)	Fixed-Grid		Flex-Grid	
	Bandwidth (GHz)	#Wave-lengths	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

There are three nodes and two links in this example. We assume that a link has 150 GHz capacity, where fixed-grid and flex-grid links would have three 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, flex-grid uses super-channel; on the contrary, in link 2, limitation of fixed-grid to 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 (2x12.5 GHz) of 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, flex-grid link occupies 37.5 GHz less spectrum in total than the fixed-grid link.

Figs. 2(c) and 2(d) represent scenarios where lightpaths originate and terminate at 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 setup between nodes A to C. This request originates and terminates into 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 (4 slots) signal. On the contrary, the second connection request of 100 Gbps originating from node B occupies only (3 slots) 37.5 GHz instead. Similarly, in Fig. 2(d), a 40 Gbps connection request occupies 2 slots (25 GHz) in link 1 but takes up 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 dotted white). 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 EON is the introduction of dynamically-adjustable modulation formats. Advanced modulation formats offer higher bit rate and spectral efficiency (bits/sec/Hz), at 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. Fig. 3 shows spectrum assignment in mixed-grid

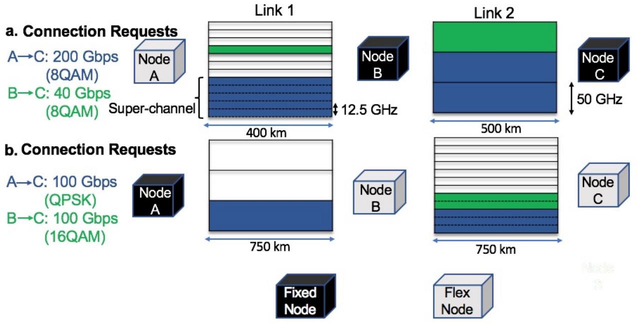

Fig. 3. Spectrum assignment in different mixed-grid scenarios using different modulation formats.

scenarios assuming spectrum occupancies for various bit rates as reported in Tables 1 and 2 [12] [18] [19] [20]. Transmission performance (e.g., reach, operating bandwidth, OSNR) 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 which considered the Gaussian Noise Model [21]. Fig. 3 has same settings as Fig. 2 with additional capability of assigning spectrum based on different modulation formats which 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), 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 (flex-grid node), it can use higher modulation format such as 8QAM which still satisfies 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 modulation format of 8QAM. With a non-distance-adaptive route and spectrum allocation technique, link 1 would need 2 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 2 slots (25 GHz) from link 2 (flex-grid) using 16QAM.

Standard strategies for resource assignment in EON 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 re-usability 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 routing and spectrum allocation policies, as shown below.

1. Routing Policies

Shortest-Path First (SPF): SPF [22] [23] pre-computes 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 pre-computed fixed route. It checks whether the desired slot is free on each link of the pre-computed route or not. The request is blocked if one link of the pre-computed route does not have the desired slot.

Most Slots First (MSF): This policy [27] keeps track of available slots at each link of a path. It pre-calculates 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 shortest path.

Largest Slot-over-Hops First (LSoHF): This policy [27] keeps track of available slots at each link and path length, which is measured in terms of hop count (links). It pre-calculates the 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 which requires least spectral allocation among 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 in Fig. 4. According to Fig. 2 and Table 1, spectrum requirement for these three paths 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 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 same. However, SEDRA chooses path 2 which has higher spectral efficiency.

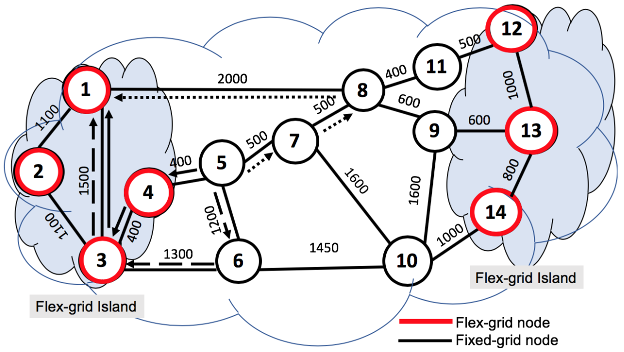

Fig. 4. Route, spectrum, and modulation-format allocation using SEDRA.

2. Spectrum-Allocation Strategies

First Fit (FF): This policy [25] 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 [26].

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 to be used too often [26]. Allocated spectrum slots are expected to be uniformly distributed over the entire spectrum.

Reusable Spectrum Allocation First (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 FF policy. If no slots are available in this list, it selects from the list of never-used slots using 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 be always DP-QPSK). In this case, k-shortest paths are calculated for minimizing number of hops, as this is the most spectrally-efficient choice; ii) distance-adaptive modulation-format assignment in which we incorporate the distances in km to calculate the shortest path. Modulation formats are selected depending 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 distance of 2300 km. According to Fig. 3 and Table 2, 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 distance-adaptive modulation format, we can use even less spectrum to provision the same lightpath request.

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

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 $V = V_{FI} \cup V_{FL}$.
- $n_s(l)$: 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 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 $\kappa_{s,d} \subseteq P_{s,d}$.
- 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 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.
- $p_{s,d}^{best}$: 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.

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 $\gamma_T^p$ 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 $\gamma_{min}^p$;
```

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) for requested $\alpha_{s,d}$. Function *spectrum_avail()* calculates contiguous slot availability for each path using function *mixed_grid_spectrum ()*, and returns 'true' if slots are available on a path. Function *mixed-grid_spectrum ()* identifies location of fixed and flex-grid nodes along the path and returns γ_l^p as required spectrum for $\alpha_{s,d}$. The paths which have the required contiguous slots are listed in a candidate path list (line 8). Now, modulation format and corresponding spectrum allocation for each of the candidate paths are calculated (lines 11-13). Modulation format for corresponding path length p^l is calculated using Table 2. For SEDRA without distance-adaptive modulation-format property, modulation format is fixed to DP-QPSK. Function *calculate_spectrum* then

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, $n \leftarrow \gamma_l^p \,/\, W_{FL}$;
     ▷ 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: $\gamma_l^p$;
if $\phi_s == 0$ then
    if $\phi_{n_s(l)} == 0$ then
        $calculate\_spectrum(0, \alpha_{s,d}, m)$
                        ▷ 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 $\gamma_l^p$;
```

Algorithm 4. calculate_spectrum()

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

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;
```

calculates the minimum spectrum required, γ^{p}_{min} on path p for $\alpha_{s,d}$. Path which requires minimum spectrum γ^{p}_{min} is called the best path, $p^{best}_{s,d}$, and modulation format used to achieve minimum spectrum allocation is denoted by m^{best} (lines 15-22).

6. ILLUSTRATIVE NUMERICAL RESULTS

Our study first considers the 14-node NSFNet topology for analysis. However, we also considered 24-node USnet backbone network topology, to verify our findings for a larger network. Selection of fixed-grid and flex-grid nodes is pre-determined in both. Half of the nodes are considered to be fixed-grid and another half to be flex-grid. Flex-grid nodes are located at east and west coastal areas. Capacity of each optical fiber link is assumed to be 5 THz. This leads to 100 wavelengths for a fixed-grid link with 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 Poisson inter-arrival and exponential holding time of mean 15 seconds are generated. Today, optical network traffic is of mostly semi-static or static 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 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 beyond 100 Gb/s with significant increase in 400 Gb/s, representing heavy load.

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 increment of normalized offered traffic load. Following are the performance evaluation metrics considered to evaluate MDRA against other strategies:

We observed BBR performance of MDRA for upto 53% offered traffic load obtaining 10% of bandwidth blocking, following the real network scenarios.

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 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 node × channel capacity in GHz × spectral efficiency of flex-grid.

where

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

Results were obtained over two US network topologies with variation in number of nodes and links. For 14-node NSFNet network, number of fixed-grid links = 14, and number of flex-grid links = 6. For 24-node USnet network, number of fixed-grid links = 29, and number of flex-grid links = 14. Spectrum utilization shows how much of the spectrum is occupied on average while we vary the offered load for different routing, spectrum allocation technique.

Spectral utilization ratio = average occupied spectrum ÷ network capacity.

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

B. Simulation Results

For a route selection problem, 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 $k = 10$.

Fig. 5 plots 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 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 41% more bandwidth requests compared to MDRA (0.07). MSF has the worst BBR performance (0.31 for 50% offered load) of all four as it does not constrain spectrum usage.

Fig. 6 compares 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 still worse than RSAF.

Fig. 7 compares performance of MDRA and SPF on spectrum utilization ratio. Although for low loads MDRA and SPF have similar spectral utilization, the difference becomes appreciable for higher loads. For 50% offered load, spectrum utilization ratios of SPF and SEDRA are 0.39 and 0.45, respectively. This shows 15% more spectrum utilization for MDRA vs. SPF.

The previous result can be justified as follows: to avoid bottleneck links, MDRA takes routes which do not always belong to the shortest path. Fig. 8 represents the average hop count taken by all four routing strategies. MDRA and SPF both allocate average number of hops around 2.4 (for low loads, below

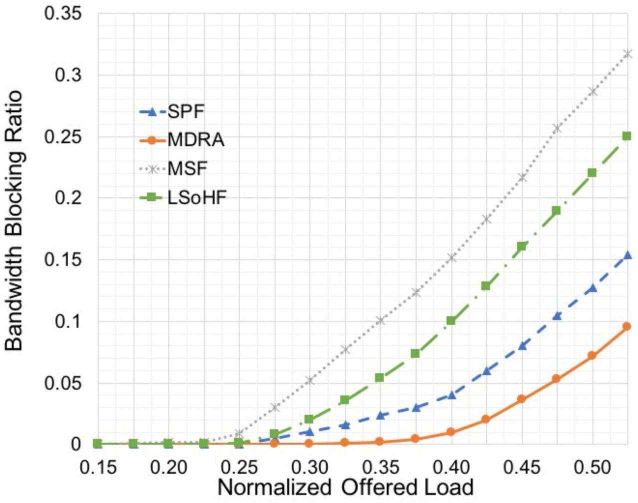

Fig. 5. Comparison of bandwidth blocking ratio (for NSFNet).

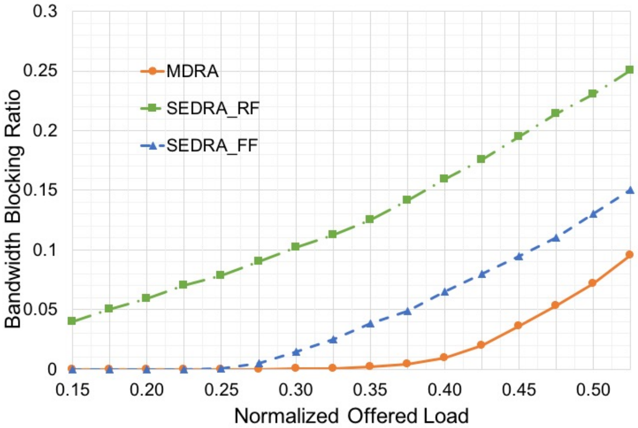

Fig. 6. Comparison of spectrum allocation strategies for NSFNet.

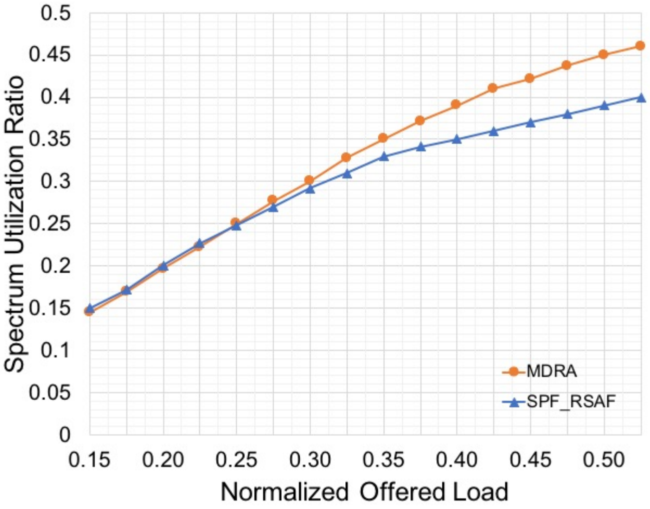

Fig. 7. Comparison of spectral utilization for MDRA and SPF (for NSFNet).

30%). The difference starts at 35% load (see Fig. 8). SPF experiences resource shortage and blocks the connection request from this point onwards. Most of the network spectrum becomes exhausted now, therefore average number of hops per connection request gradually decreases (to 2.3 in SPF). MDRA with comparatively lower blocking ratio takes longer routes (upto 2.56 average hop count) to allocate requests when shorter paths are congested. As MSF does not minimize spectrum allocation, and only focuses on paths with highest available spectrum, it takes longer paths (upto 6 hops) compared to all four strategies. LSoHF does balance between provisioning shorter path with highest availability. Therefore, the average hop count (upto 4.3 hops) is lower than MSF but not lower than SPF and MDRA. In summary, for 50% offered load, MDRA achieves 41% lower BBR than SPF, with the cost of 11% increased hop count.

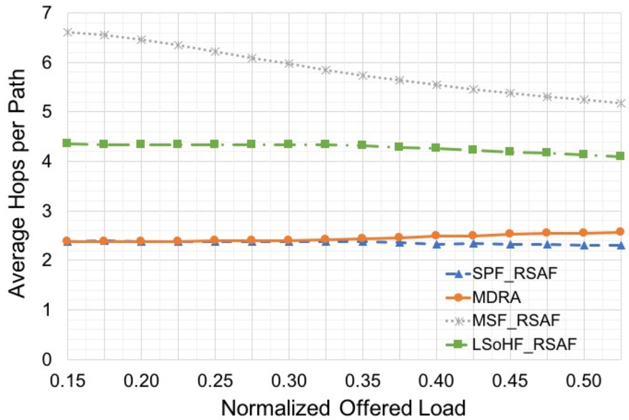

Fig. 8. Comparison of average hop count among different routing strategies for NSFNet.

Fig. 9 shows a breakdown of lightpath blocking for traffic demands with different bit rates. All routing strategies block 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.

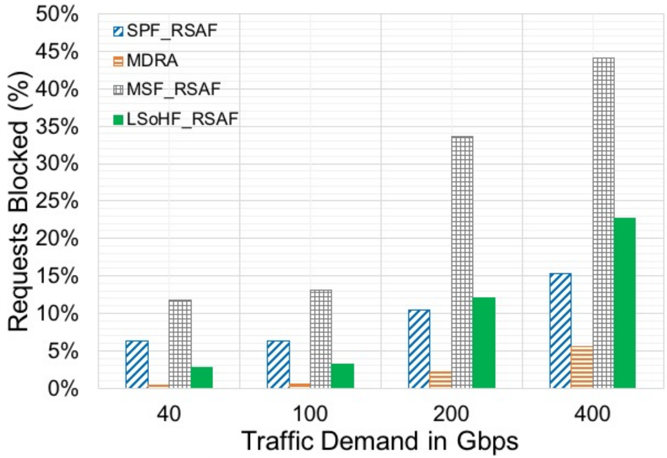

Fig. 9. Requests blocked from individual bit rates for NSFNet.

Fig. 10 compares BBR of MDRA and SPF with and without distance-adaptive modulation-format allocation (denoted with DA in the figure). Inclusion of 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 37% for MDRA and only 15% for SPF).

Fig. 11 considers a migration scenario where number of flex-grid nodes is increased gradually. Here, a comparison of BBR is done by setting an increasing number of flex-grid nodes for

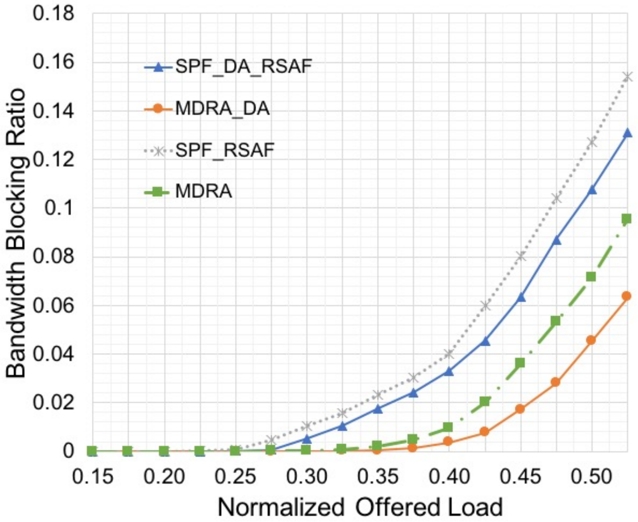

Fig. 10. Comparison of BBR with and without distance-adaptive modulation for NSFNet.

MDRA and MDRA_DA. It is already shown that MDRA_DA has lower BBR than MDRA without DA modulation format. Number of flex-grid nodes also plays a role in BBR performance of MDRA. As the number of flex-grid nodes grows, capacity of a network to accommodate more connection requests also grows.

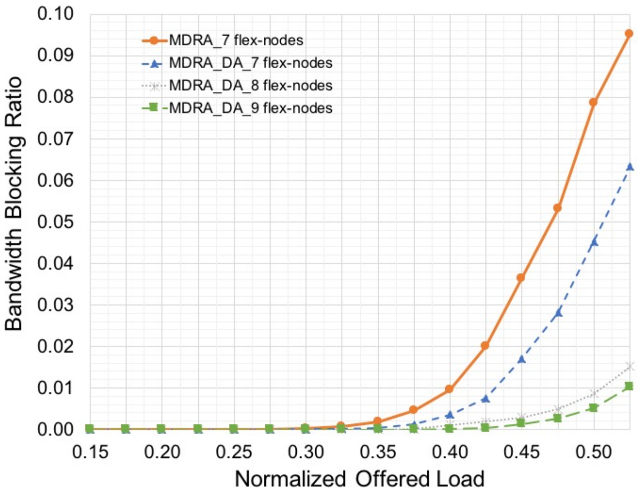

Fig. 11. Comparison of BBR with varying flex-grid nodes (for NSFNet).

Fig. 12 depicts BBR comparison between with and without distance-adaptive modulation formats in a 24-node USNet topology. Observations seen for 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 without DA modulation formats (at 50% offered load). USnet topology, having 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 upto 41% BBR reduction compared to baseline solutions. Also, 37% BBR reduction is achieved with DA modulation-format allocation compared to non-DA approach. We also performed detailed analysis of impact from different traffic profiles, number of flex-grid nodes, modulation formats, and network topology, to gain more insights on RSMA for mixed-grid networks.

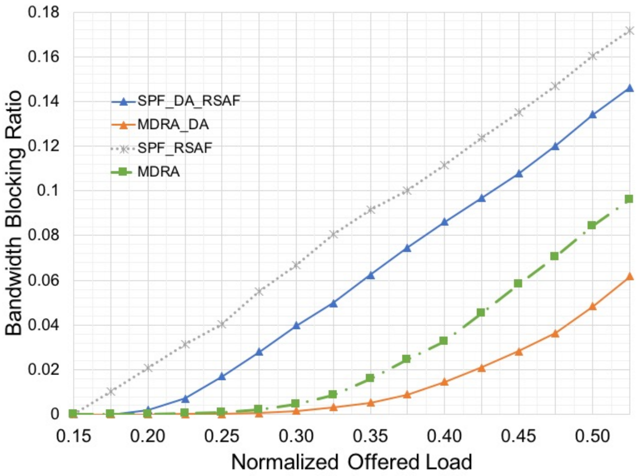

Fig. 12. Comparison of BBR with and without distance-adaptive modulation-format for USNet.

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