Dynamic Routing and Spectrum Assignment in Co-Existing Fixed/Flex-Grid Optical Networks

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***Abstract*— A traditional wavelength-division multiplexed (WDM) backbone network with its rigid features is unsuitable for emerging diverse and high bitrate (400 Gb/s, 1 Tb/s) traffic needs. Flexible solutions employ new technologies such as bandwidth-variable optical cross connects (BV-OXC) with liquid crystal (LCoS) wavelength-selective switches (WSS), sliceable bandwidth-variable transponders (SBVT), etc. in a flex-grid network. Flex-grid network operates on variable spectral granularities (e.g., 12.5 GHz), and higher modulation formats (quadrature amplitude modulation). However, a greenfield deployment of flex-grid technologies may not be practical, due to cost of technology and usability. This leads to a brown-field network where both fixed-grid and flex-grid technologies co-exist with seamless interoperability. Thus traditional traffic routing and resource allocation techniques need to evolve in a mixed-grid infrastructure. Our study considers the dynamic routing and spectrum assignment (RSA) problem in a fixed/flex-grid co-existing optical network. It provisions routes for dynamic, heterogeneous traffic, ensuring maximum spectrum utilization and minimum blocking.**

Keywords—Flex-grid, Routing and spectrum assignment (RSA), Resource allocation, Mixed-grid.

I. INTRODUCTION

Cisco global visual networking index (VNI) forecast for 2016-2021 predicts massive growth in emerging technologies such as machine-to-machine (M2M) connections growing 17 billion to 27.1 billion, virtual reality (VR) / augmented reality (AR) traffic increasing 20 folds, and live Internet video increasing 15 folds [1]. To prevent existing ITU-based fixed-grid networks from being exhausted by this heterogeneous and high-volume traffic, spectrum-efficient resource provisioning is critical. Major drawback of the fixed-grid network is the use of fixed spectrum slots (50, 100 GHz, etc.) regardless of the spectrum demand, leading to poor spectrum utilization. Flex-grid offers finer sub-granularities and super-channeling ability by providing adjustable use of any multiple of finer slots of spectrum (12.5, 25, 50, 75, 87.5 GHz, etc.). Thus, while allocating resources unlike fixed-grid, flex-grid can accommodate any number of slots based on the source, destination, and intermediate node type (fixed/flex-grid) on the path. Ref. [2] shows that, on datacenter interconnections of Telefonica network, there are significant amount of free capacity left with SBVT compared to zero free capacity left with fixed transponders during traffic peak hours.

Although there is acceptance of the benefits of flex-grid, there is debate on whether a complete migration is needed to achieve those benefits. The introduction of new flex-grid switching equipment by adding new fibers leads to a greenfield migration. On the contrary, a less-aggressive migration strategy would be where nodes with flex-grid switching capabilities will co-exist with fixed-grid nodes for some time, before complete migration. The intermediate step where both fixed and flex-grid nodes will coexist poses new challenges. Traditional routing and spectrum assignment (RSA) techniques can no longer achieve the optimal results in this complex scenario. Thus, it is crucial to study effective strategies for RSA in co-existing fixed/flex-grid networks (hereafter referred as "mixed-grid" case). Most prior studies on RSA considered either all fixed-grid or all flex-grid scenario, thus failing to capture the complexity of mixed-grid scenarios. A few prior works proposed mixed-grid RSA strategies under static traffic loads [3-4]. Ref. [5] studies RSA problem under dynamic traffic, but it limits the analysis to adaptive shortest-path routing.

Addressing the constraints of mixed-grid scenario, we propose a novel dynamic algorithm where RSA decisions are taken to obtain minimum bandwidth blocking on overall network. In a mixed-grid network, shortest path first fit (SP-FF) is not always the optimal solution for RSA. RSA decision depends on the number and the sequence of fixed and flexible nodes on a lightpath. Our proposed Spectrum-Efficient Dynamic Routing and spectrum Assignment (SEDRA) algorithm ensures allocation of routes and spectrum to minimum bandwidth requiring paths.

The rest of this study is organized as follows. In Section II, we give an illustrative example of spectrum allocation in different network scenarios. Section III describes the proposed algorithm (SEDRA). Section IV contains simulation setup and performance analysis. Section V concludes the study.

II. ILLUSTRATIVE EXAMPLE

As discussed above, before complete migration to flex-grid network, an intermediate mixed-grid is more practical. Fig. 1 shows an example of such a network topology where both fixed- and flex-grid nodes co-exist. Nodes 2, 3, 4, 12, 13, and 14 are flex-grid nodes and the rest are fixed-grid nodes.

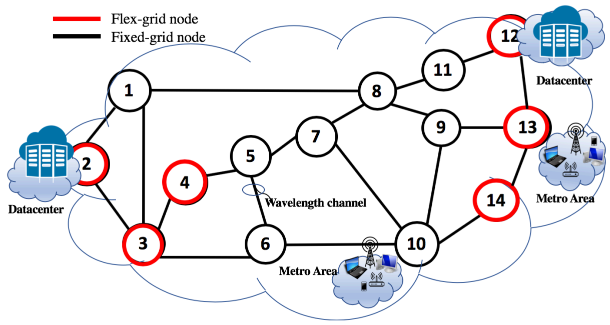

Fig.1 Co-existing fixed/flex-grid in NSFNet topology.

Fig. 2 demonstrates spectrum assignment in different mixed-grid scenarios. We consider 50 GHz slot-width for fixed-grid and multiple of 12.5 GHz slot-width for flex-grid. We also assume modulation format to be fixed to DP-QPSK (Dual Polarization Quadrature Phase Shift Keying) with 28 GBaud. The spectrum occupation of client signals of various bit-rates are reported in Table I. In addition, we assume that fixed-grid nodes are equipped with wavelength converters. In Fig. 2(a), a lightpath request of 100 Gb/s starts at a fixed-grid node, and traverses through two fixed-grid nodes. On both links, we need a 50 GHz (one fixed-grid slot) channel to carry this 100 Gb/s request. In Fig. 2(b), for the same 100 Gb/s request, only 37.5 GHz (three flex-grid slots) is sufficient on the second link, as the 2nd and 3rd nodes are flex-grid nodes. If the destination node were a fixed-grid node, then the same 50 GHz would continue through the second link. Similarly, in Fig. 2(c), for a 200 Gb/s request, all the nodes being flex-grid, only 75 GHz (six slots) is required over both links. If the source were a fixed-grid node, it would need to allocate 50 GHz channel (four fixed-grid lightpaths). In Fig. 2(d), a 40 Gb/s request starting from a flex-grid node occupies 25 GHz (two flex-grid slots). However, the following fixed-grid link requires 50 GHz (one fixed-grid slot), as it is the slot-width of a fixed-grid node. For requests less than 100 Gb/s, fixed-grid overprovisions the spectrum.

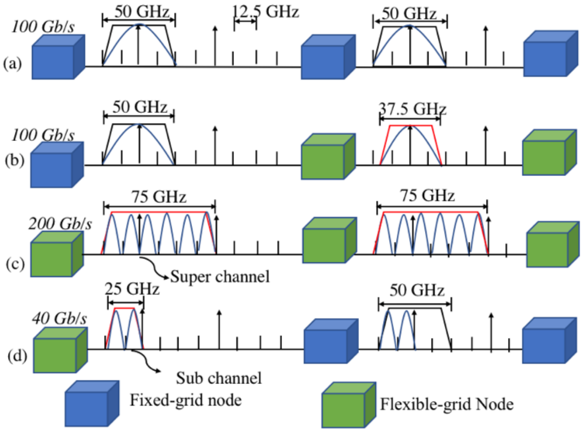

Fig. 2 Spectrum assignment in different mixed-grid scenarios.

Table I: Spectrum occupation for various bit rates.

Traffic Demand (Gb/s)	Fixed-Grid		Flex-Grid	
	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	125	10

We demonstrate the RSA problem in a mixed-grid optical network using an illustrative example. In Fig. 1, consider a 100 Gb/s traffic demand from source node 10 to destination node 12. We take three shortest paths and calculate spectrum required on each path. Let guard band be 12.5 GHz for each channel. A 100 Gb/s request requires one slot (50 GHz) for flex-grid and three slots (37.5 GHz) for flex-grid nodes (see Table I). According to Fig. 2, spectrum requirement for the three paths can be calculated as follows:

- Path 1, 10-14-13-12 (one fixed and three flex nodes): (50+12.5+37.5*2+12.5*2) GHz = 162.5 GHz
- Path 2, 10-9-13-12 (two fixed and two flex nodes): (2*50+2*12.5+37.5+12.5) GHz = 175 GHz
- Path 3, 10-9-8-11-12 (four fixed and one flex nodes): (4*(50+12.5)) GHz = 250 GHz

Evidently, path 1 is the most spectrally-efficient route for the request. Although paths 1 and 2 both have the same number of links, path 2 will waste more spectrum. Path 3 uses one extra link and one extra fixed-grid node which increases the required spectrum. Therefore, RSA algorithm needs to be aware of the source/destination nodes, intermediate nodes, and corresponding spectrum usage.

III. Method: SEDRA

Our method (SEDRA) selects the path and slots which use minimum spectrum, leading to reduced bandwidth blocking for the overall network. Network topology (N(V,E)), locations of fixed-grid nodes (L_f) and flex-grid nodes (L_{fl}), slot width of fixed- (W_f) and flex-grid links (W_{fl}), guard bands (G_f, G_{fl}), and traffic profiles are given as inputs. Output will be the best path (s) with lowest spectrum usage for a given demand between a source-destination pair under current network state.

For a given network topology and traffic demand, SEDRA first finds k-shortest paths for a source-destination pair (line 2). These candidate shortest paths (P) are found based on available capacity of links (i.e., excluding links without enough capacity). For each of these paths, fixed/flex-grid nodes are identified from the topology (line 3a). Next, spectrum usage (S(p)) is calculated for each path by identifying required number of slots (Fig. 2 and Table. 1) and corresponding spectrum usage for each slot including guard-bands (line 3b). Finally, it compares spectrum usage of all the paths, finds the best solution (s) with lowest spectrum usage (line 4), and allocates resources accordingly (line 5). Hence, traffic will always be assigned to lowest-spectrum path, ensuring maximum usage of the network capacity. SEDRA pseudocode is reported in Algorithm 1.

Algorithm 1: Spectrum-Efficient Dynamic Routing and spectrum Assignment (SEDRA)

Input: Network topology N (V, E), location of fixed-grid nodes $L_f \in$ V, location of flex-grid nodes $L_{fl} \in$ V, slot width of fixed-grid links (W_f) and flex-grid links (W_{fl}), guard band of fixed-grid links (G_f) and flex-grid links (G_{fl}).
Output: Path and slots used on each link for a given traffic demand which minimizes spectral usage.

1. **for each** new connection request *r (src, dst, required_spectrum, traffic_profile)* **do**:
2. Find set of non-blocking k-shortest paths, P for the given *r.src* $\in$V and *r. dest* $\in$ V;
3. ***for each*** path, $p \in$ P ***do***:
   a. Locate fixed-grid nodes $\in L_f$ and flex-grid nodes $\in L_{fl}$, along path p;
   b. S(p) = calculated spectrum usage for all fixed-grid and flex-grid links based on number of slots required for each type of links using W_f, W_{fl}, G_f and G_{fl};
4. **end for**;
5. Find path, s = lowest (S(p)), which needs lowest bandwidth among all paths in P;
6. Allocate spectrum and route for the given traffic along s;
7. **end for**;

IV. Illustrative Numerical Examples

Our study considers the NSFNet backbone network topology (see Fig.1), where selection of fixed-grid and flex-grid nodes are also shown. Capacity of each optical fiber link is assumed to be 4 THz spectrum in each direction. This leads to 80 frequency slots for a fixed-grid link with slot-width of 50

GHz. Each flex-grid link will have 320 frequency slots, each of 12.5 GHz. For traffic demand, we generated any-pair connection requests with Uniform and Poisson inter-arrival and exponential holding time. To represent heterogeneous traffic, we considered three different traffic profiles shown in Table II. 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. In Fig. 3 and Fig. 4 the maximum connection request is 140,000 and the offered load is normalized with respect to load of the maximum connection request. Connection requests are handled by an event-based simulator to capture dynamic scenario.

Table II: 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%

To analyze the performance of the proposed method, we compare bandwidth blocking ratio (BBR) of SEDRA and SS-FF. BBR is defined as the ratio of rejected bandwidth over total requested bandwidth. This is an important metric for mixed-grid networks. Depending on the requested spectrum, choosing fixed-grid vs. flex-grid node makes a huge difference in *wastage of spectrum*, which comes from guard bands and unused spectrum in a selected slot. When this *wasted spectrum* becomes large, the nodes reject/block incoming requests due to capacity limit.

In Fig. 3, for 71% of Uniformly-distributed offered load and traffic profile 1, SEDRA (BBR 0.0007) achieves significantly lower BBR compared to SP-FF (BBR 0.0263). With increasing load, both SEDRA and SP-FF block more requested bandwidth. However, SEDRA, being aware of spectrum waste, reduces bandwidth blocking by 6% than SP-FF. We observe similar trends for traffic profile 2 as well. For the heavy loaded traffic profile 3, SEDRA reduces bandwidth blocking by 4.4% than SP-FF. Here, we considered offered load within 70-100% to avoid BBR values which are zero or more than 25% for SEDRA.

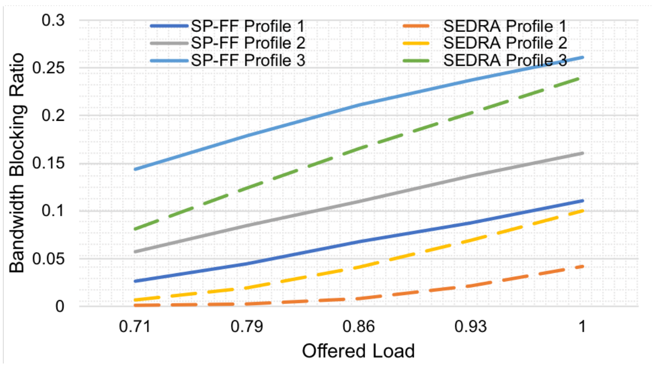

Fig. 3 Bandwidth blocking ratio vs. offered load for Uniform distribution.

In Fig. 4, we observe significant reduction of BBR using SEDRA than SP-FF for all three traffic profiles of Poisson distribution. Profile 1 shows the lowest blocking among other profiles as 50% of the requests are only 40 Gb/s. Profile 3 shows the highest blocking as it mostly contains requests beyond 100 Gb/s. On average, SEDRA reduces BBR by 3% more than SP-FF for all three profiles. Here, we considered offered load within 50-100% to avoid BBR values which are zero or more than 20% for SEDRA.

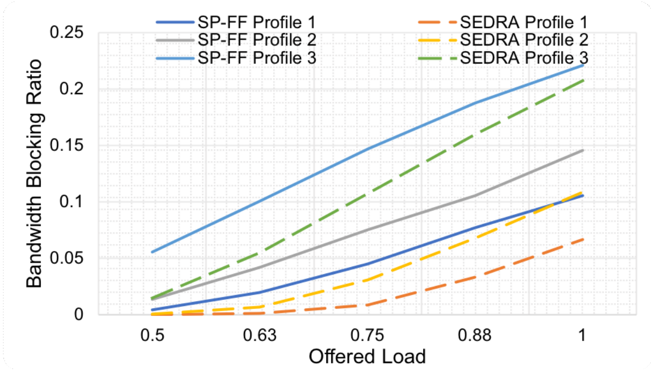

Fig. 4 Bandwidth blocking ratio vs. offered load for Poisson distribution.

V. Conclusion

A mixed-grid spectrum-efficient route selection method was presented for a dynamic scenario. Our proposed method routes heterogeneous traffic with lowest spectrum waste in a mixed-grid scenario. Illustrative results show significant improvement compared to a traditional algorithm (SF-FF) in terms of BBR. Our study demonstrates how a mixed-grid-aware solution can improve over traditional solutions. Future studies should consider other metrics such as throughput and spectrum utilization. Gradual migration from fixed-grid to flex-grid using resource disaggregation is another important direction yet to be explored.

Acknowledgement

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