Provisioning Super-channel Lightpaths in an Optical Network Subject to 50-GHz Central Frequency Alignment

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***Abstract*—Provisioning super-channel lightpaths in an optical network with 50-GHz spectrum grids is subject to the constraint of aligning lightpath central frequencies to the grids, which is however often ignored in many studies. In this study, we consider lightpath provisioning with different spectrum granularities subject to such a constraint. Two spectrum assignment strategies are developed and simulation results show that the granularity-based strategy is effective to reduce the maximum number of 50-GHz grids used and spectrum fragments generated.**

***Keywords*—super-channel, lightpath provisioning, spectrum assignment, central frequency alignment**

I. Introduction

The rapid growth of traffic demands requires lightpaths in optical networks to provide higher bandwidth (e.g., 400-Gb/s and 800-Gb/s super-channels). As such, the bandwidth of lightpaths is gradually expanded from the standard ITU-T grids (e.g., 50 GHz or 100 GHz) to 150 GHz and even 200 GHz [1][2]. It is likely that lightpaths with different spectrum granularities will coexist in a future optical network. In the literature, there have been many studies focusing on routing and spectrum assignment (RSA) in elastic optical networks (EONs) [3][4], in which the spectrum assignment of lightpaths is assumed to be based on a fine granularity, e.g., 12.5 GHz, and the central frequency of each provisioned lightpath is only required to be aligned with one of these fine granularities. Nonetheless, in today's optical networks, there are many old WSSs, which requires a lightpath to be established based on a certain coarse frequency grid, e.g., 50-GHz grid. And the central frequency of a provisioned lightpath cannot be assigned as flexibly as in EON, but needs to be aligned with the 50-GHz coarse grid. This therefore brings in a new constraint of central frequency alignment in addition to the well-known constraint of wavelength continuity. With such a new constraint, it is challenging to align the spectra of lightpaths with different spectrum granularities (e.g., 100 GHz, 150 GHz, and 200 GHz), and some spectrum fragments and wastage will occur if the lightpaths are not properly assigned with spectra.

In this paper, we consider the lightpath provisioning problem subject to the constraint of lightpath central frequency alignment with the 50-GHz grid. We specifically propose two spectrum assignment strategies (i.e., node pair-based and granularity-based strategies) to solve the problem, and their performance is evaluated and compared in terms of spectrum usage and fragmentation. Simulation results show that the granularity-based strategy is more efficient in spectrum assignment and shows a lower spectrum resource usage and fragmentation.

This work was jointly supported by the supported by the National Key R&D Program China (2022YFB2903700), the National Natural Science Foundation of China (NSFC) (62271338), and the Natural Science Foundation of Jiangsu High Educational Institutions (22KJB510041).

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II. Lightpath Provisioning with Central Frequency Alignment

An optical network using the conventional fixed-grid WSSs requires all the provisioned lightpaths to align their central frequencies with a certain frequency grid (e.g., 50 GHz), i.e., the constraint of central frequency alignment. Based on the 50-GHz grid, Fig. 1 shows a layout of lightpath spectra of different granularities, ranging from 50 GHz to 200 GHz. Specifically, for the 50-GHz granularity, the whole super C band (6 THz) can accommodate the largest number (i.e., up to 120) of optical channels subject to the constraint of central frequency alignment. Assuming that n is the index of a central frequency in the 50-GHz grid, the indexes of optical channels of the other three granularities in the super C band can be calculated by (1)-(3), respectively.

$$F_{100} = 2 \times n, n \in 1 \ldots \frac{K}{2} \tag{1}$$

$$F_{150} = 3 \times n - 1, n \in 1 \ldots \frac{K+1}{3} \tag{2}$$

$$F_{200} = 4 \times n - 1, n \in 1 \ldots \frac{K+1}{4} \tag{3}$$

Here, K is the total number of 50-GHz optical channels. F_{100}, F_{150}, and F_{200} are the indexes of central frequencies of 100-GHz, 150-GHz and 200-GHz optical channels relative to the 50-GHz grid, respectively. For example, for the first 100-GHz optical channel, its index of central frequency is 2, as shown in Fig. 1, with a 25-GHz spectrum unused on the left. Similarly, for the first 150-GHz optical channel, its index of central frequency is also 2, with a perfect alignment with the 50-GHz grid. A similar observation can be made for the 200-GHz granularity in Fig. 1. Thus, we can find that their total numbers of optical channels supported by the super C band are 60, 40, and 30, respectively.

Based on the spectrum layout in Fig. 1, it is clear to see that there is significant mismatch between the left and right spectrum boundaries of optical channels with different spectrum granularities. This would potentially lead to serious fragmentation when provisioning lightpaths subject to the constraint of central frequency alignment. Fig. 2 illustrates such examples on how the optical channels with different bandwidth granularities can form spectrum fragments on a fiber link. We assume that there are four 100-GHz and two 150-GHz optical channels. Fig. 2 compares two provisioning scenarios, i.e., *S1* and *S2*. *S1* sets up the optical channels according to their original order. *S2* sets up the optical channels based on their spectrum granularities from the smallest to the largest. In *S1*, we note that there is a 25-GHz spectrum fragment between neighboring 100-GHz and 150-GHz optical channels. This fragment cannot be used by any other lightpath services. As such, the maximum number of 50-GHz grids occupied is 17 and the sum of spectrum fragments is 125 GHz in *S1*. In contrast, the maximum number of 50-GHz grids occupied is 15 and the sum of spectrum fragments is only 50 GHz in *S2*, significantly less than *S1*. This example shows that different spectrum assignment strategies can lead to different spectrum resource usage and spectrum fragmentation. Thus, to improve spectrum utilization, it is critical to design an efficient spectrum assignment strategy to assign spectra for lightpaths with different spectrum granularities.

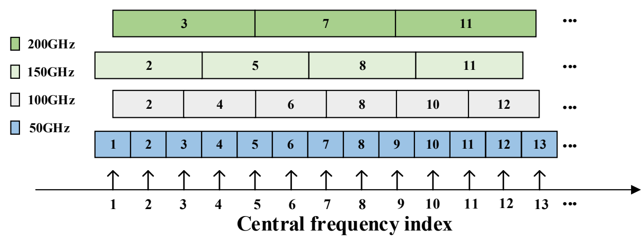


Fig. 1. Spectrum layout of optical channels.

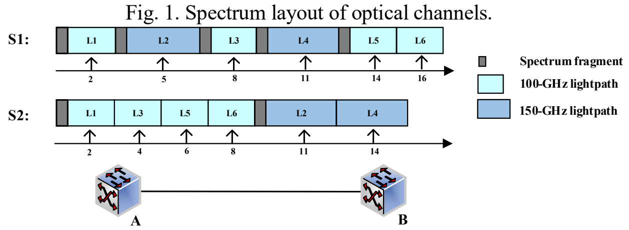


Fig. 2. Examples of different spectrum assignment strategies.

III. Central Frequency-Aligned Spectrum Allocation

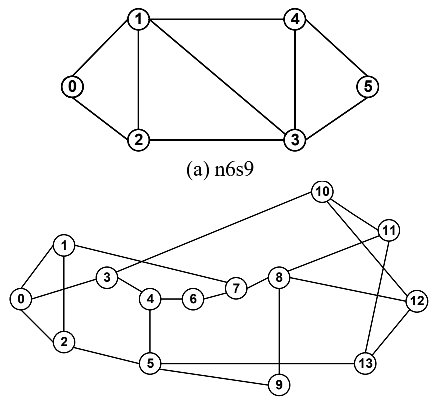
Based on the previous example, we note that spectrum fragmentation is closely related to lightpath spectrum allocation and it is significant to develop an efficient strategy to tackle the spectrum mismatch between lightpaths with different spectrum granularities. For this, we consider the lightpath routing and spectrum assignment strategy as follow. Specifically, for lightpath routing, we assume that each lightpath is always established along its shortest route. For spectrum assignment, we consider the following two strategies, in which in addition to the constraint of spectrum continuity, the constraint of central frequency alignment needs to be guaranteed.

Node Pair-Based Strategy: In a network, there are multiple node pairs, each of which may have more than one lightpath request with different spectrum granularities. This strategy employs the first-fit strategy (i.e., the first available spectrum grid) to sequentially provision each lightpath of each node pair following a certain node-pair order.

Granularity-Based Strategy: This strategy first sorts all the lightpaths with the same granularities from different node pairs in the same lists, and then sequentially provision lightpaths in the lists based on their spectrum granularities. We may do this from the smallest to the largest granularities, or following other specific orders. For each of the lists, we assign spectra for lightpaths one by one following their individual shortest routes. When all the lightpaths in a list are provisioned, we find the largest central frequency index of all the provisioned lightpaths f_{max}. When the lightpaths in the next list are provisioned, then their assigned central frequency indexes must be greater than f_{max}. This process is repeated until all the lightpaths in the lists are provisioned. Here we try to provision lightpaths with different spectrum granularities using different wavelength bands with each f_{max} as a boundary. In each band, all the lightpaths with the same granularity are provisioned. By doing this, we can avoid the bandwidth mismatch between lightpaths with different spectrum granularities, thereby minimizing spectrum fragmentation.

IV. Simulations and Performance Analyses

We consider two test networks, i.e., a six-node, nine-link n6s9 network and a 14-node, 21-link NSFNET network for simulation studies. We assume that the total spectrum in each fiber link is 6 THz (corresponding to the super C band), and 50 GHz is employed as a basic spectrum grid, to which the central frequency of each lightpath should be aligned. There are three bandwidth granularities, i.e., 100 GHz, 150 GHz, and 200 GHz, which corresponds to 60, 40, and 30 optical channels in the whole super C band, respectively. In n6s9, the number of lightpaths between each node pair is randomly generated within the range of [3, 6], and in NSFNET, given a fixed total number of lightpaths in the whole network (ranging from 60 to 150), each lightpath is randomly assigned to a node pair.

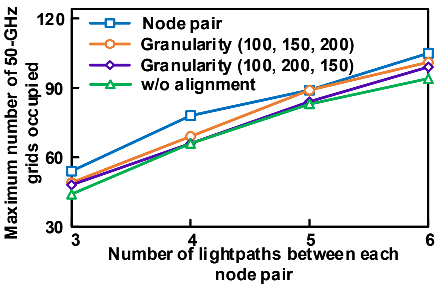


(a) n6s9

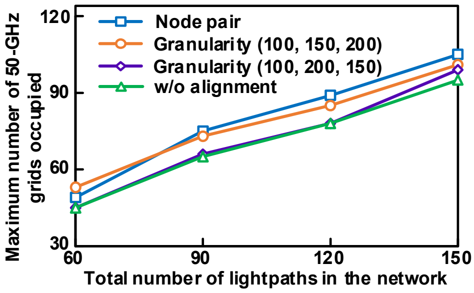
(b) NSFNET

Fig. 3. Test networks.

We first evaluate the *maximum number of 50-GHz grids occupied* in the whole network. Fig. 4 shows the results of n6s9 and NSFNET, in which the legends of "Node pair," "Granularity," and "w/o alignment" correspond to the node pair-based and granularity-based spectrum assignment strategies, and the case without the constraint of central frequency alignment, respectively. For the "Granularity" scheme, we specifically consider two granularity orders of lightpath provisioning, i.e., (100, 150, 200) GHz and (100, 200, 150) GHz. For n6s9, we note that with increasing number of lightpaths between each node pair, the maximum number of 50-GHz spectrum grids used also increases. This is because more lightpaths need to be set up, which leads to more spectrum resources used. In addition, comparing the two strategies, the granularity-based strategy shows a smaller number of occupied 50-GHz spectrum grids and it is very efficient to perform close to the "w/o alignment" case. This is because the granularity-based strategy sorts lightpaths based on their granularities and uses a common waveband to provision lightpaths of the same granularity, which minimizes spectrum fragmentation due to the spectrum mismatch between different granularities. In addition, comparing the two granularity orders of lightpath provisioning, we note that the order of (100, 200, 150) GHz outperforms the order of (100, 150, 200) GHz. This is because there is spectrum mismatch between 150-GHz and 100-GHz lightpaths and 150-GHz and 200-GHz lightpaths. In contrast, between 100-GHz and 200-GHz, there is no such mismatch since a 200-GHz lightpath is essentially equivalent to two 100-GHz lightpaths according to Fig. 1. Thus, provisioning 100-GHz and 200-GHz lightpaths in adjacent bands can achieve better performance. Similar studies were conducted for NSFNET, whose results are shown in Fig. 4(b). Overall, we observe the same performance trend as in n6s9. The granularity-based strategy achieves better performance and performs very close to the "w/o alignment" case, and the order of (100, 200, 150) GHz outperforms the order of (100, 150, 200) GHz.



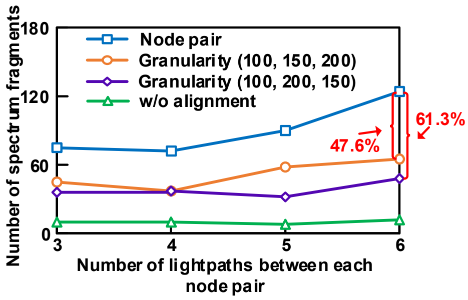
(a) n6s9



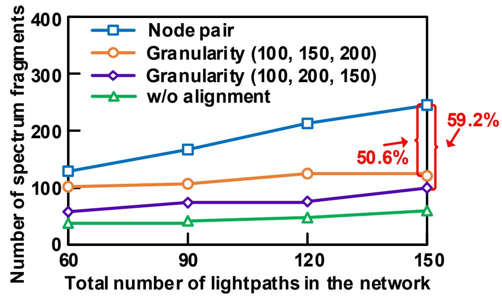
(b) NSFNET

Fig. 4. Spectrum usage.

We also evaluate the performance of the two strategies in terms of *spectrum fragmentation*, which is defined as the sum of the spectra that cannot be used to establish any lightpath on all the fiber links in the whole network. Fig. 5 shows the results of n6s9 and NSFNET. For n6s9, the granularity-based strategy always shows a smaller number of spectrum fragments compared with the node pair-based strategy, which are up to 47.6% and 61.3% reductions for the two spectrum granularity orders, respectively. Also, for the granularity-based strategy, the provisioning order of (100, 200, 150) GHz outperforms the order of (100, 150, 200) GHz. For NSNET, we have similar results to those of n6s9. Specifically, the granularity-based strategy can reduce spectrum fragmentation up to 50.6% and 59.2% under the two spectrum granularity orders, respectively. These performance differences are attributed to the same reason as for the maximum spectrum usage. Finally, comparing the performance of the granularity-based strategy and the "w/o alignment" case, we note that the latter has fewer fragments since it is the more flexible in spectrum assignment, not subject to the constraint of lightpath central frequency alignment. However, although there is a reasonably large performance difference between the two schemes in n6s9, this difference becomes smaller in the larger NSFNET, which therefore also verifies the efficiency of the granularity-based strategy in reducing spectrum fragments.



(a) n6s9



(b) NSFNET

Fig. 5. Spectrum fragmentation.

V. Conclusion

Provisioning super-channel lightpaths in an optical network with 50-GHz grid is subject to the constraint of central frequency alignment to the grid. This leads to an important issue of spectrum fragmentation when provisioned lightpaths have different spectrum granularities. To tackle this issue, we developed two spectrum assignment strategies in the context of the problem of routing and spectrum assignment. We evaluated the performance of the proposed strategies in terms of spectrum usage and fragmentation by simulations. Results show that the proposed granularity-based strategy is effective to reduce the number of 50-GHz spectrum grids used and significantly minimize spectrum fragmentation compared with the benchmark node pair-based strategy.

References

[1] N. Sambo *et al.*, "Transport network upgrade exploiting multi-band systems: S-versus E-band," in Proc. *OFC 2022*.

[2] V. Lopez *et al.*, "Optimized design and challenges for C&L band optical line systems," *IEEE/OSA Journal of Lightwave Technology*, vol. 38, no. 5, pp. 1080-1091, Mar. 2020.

[3] G. Shen *et al.*, "Quasi-CWDM optical network: cost effective and spectrum efficient architecture for future optical networks (invited)," in Proc. *ONDM 2015*.

[4] T. Ahmed *et al.*, Dynamic routing, spectrum, and modulation-format allocation in mixed-grid optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 12, no. 5, pp. 79-88, May 2020.