PAPER

Fragmentation-Minimized Periodic Network-Bandwidth Expansion Employing Aligned Channel Slot Allocation in Flexible Grid Optical Networks

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SUMMARY We propose an efficient network upgrade and expansion method that can make the most of the next generation channel resources to accommodate further increases in traffic. Semi-flexible grid configuration and two cost metrics are introduced to establish a regularity in frequency assignment and minimize disturbance in the upgrade process; both reduce the fragmentation in frequency assignment and the number of fibers necessary. Various investigations of different configurations elucidate that the number of fibers necessary is reduced about 10–15% for any combination of upgrade scenario, channel frequency bandwidth, and topology adopted.

key words: *semi-flexible grid, periodic network upgrade, fragment mitigation*

1. Introduction

Due to the rapid takeup of high-resolution video streaming including 4K/8K television and cloud-based services, Internet traffic is still increasing exponentially. Current optical networks generally employ 10/40/100 Gbps channels, and 400 Gbps/1 Tbps [1], [2] and 64 G+ baud rate channels will be widely deployed in the near future. The conventional 10/40/100 Gbps channels are aligned on fixed grids with 50/100 GHz spacing. As wider frequency bandwidths (> 50 GHz) are needed for next-generation 400+Gbps channels, future optical networks must introduce the ITU-T flexible grid with 12.5 GHz bandwidth assignment granularity [3], [4]. As flexible-grid-ready LCOS (liquid crystal on silicon) based WSSs (wavelength selective switches) have been widely deployed, the deployment of such broader capacity channels is now in progress. However, even though these next-generation channels improve the spectrum utilization efficiency, the fiber capacity is now approaching the theoretical limit [5]. As a result, the installation of new optical fibers in each network, which is an extremely costly operation, is inevitable, and thus, we are obliged to pursue further increases in the spectrum utilization efficiency to minimize this installation.

The non-uniform frequency bandwidth assignment expected of next-generation channels will cause severe frequency fragmentation; unused frequency fragments are generated over the band, which degrades the spectrum utilization efficiency of flexible grid optical networks. There are many network design and control issues in flexible grid networks; for example a survey [6] summarizes the problems and provides the evaluation of complexities. Typical goals of these studies include minimization of the number of fibers necessary to accommodate given paths or the path-blocking probability subject to given channel configuration and traffic intensity. While flexible frequency bandwidth assignment can cause fragmentation, it does offer the possibility of manipulating channel frequency bandwidth by the introduction of distance-adaptive modulation [7]. By using signal regenerators at appropriate nodes, channel bandwidths can be further squeezed [8]. So far, entropy-based metrics for fragmentation evaluation have been proposed and studied [9], [10]. For dynamic path operation scenarios, we cannot optimize the routes and spectra of all paths simultaneously; the room for spectrum assignment optimization is limited and severe fragmentation is inevitable. Re-optimization of routing and spectrum assignment through bridge-and-role or make-before-break operations was proposed for fragmentation mitigation [11], [12]. Traffic carried by the optical paths causing fragmentation is moved to newly established paths and the old paths are then torn down. Dynamic and simultaneous tuning of carrier frequencies at each pair of transponder and receiver [13], [14] can mitigate the fragmentation [15] without using additional transponders/receivers for the make-before-break operations. A simple but effective way to suppress the fragmentation is to concentrate paths with the same frequency bandwidth to a dedicated frequency block. Our early study on a static design for flexible grid networks with distance-adaptive modulation [16] successfully reduced the fragmentation. The method focuses on accommodating optical paths with the largest frequency bandwidths so that these paths are regularly aligned in the frequency domain and frequency gaps between paths are minimized. It repeats this operation until the smallest bandwidth paths are accommodated. The other study [17] divides the available frequency range into several ranges, each of which is dedicated to paths with the same frequency bandwidths. The use of multiple regular grids [18]–[20] has been shown to be effective; each is dedicated to paths of the same frequency bandwidth and

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the bandwidth gives the corresponding grid spacing. Paths are forced to be aligned on the grids and the fragmentation is well suppressed in both static and dynamic scenarios.

Network operations will need to be continued across several channel generations, where the traffic growth ratio will still exceed the fiber capacity enhancement. Thus, iteratively upgrading current channels to higher bit rate ones that occupy larger frequency bandwidths, in addition to new fiber installations, will be mandatory. During such an upgrade, the wavelength/spectrum resources assigned to channels that are not being upgraded must be fixed to avoid any service disruption, and thus, the optimal frequency/wavelength assignment will divert from the current one after several channel-upgrades. As a result, severe frequency fragmentation can develop. We need fragmentation mitigation that is effective not only for a snapshot, but also over the network's lifetime.

In this paper, we propose a channel speed upgrade and network expansion strategy that adopts the semi-flexible grid [19], [20]. This grid uses a dedicated unique grid for each channel capacity; the regularity given by the channel alignment has been proven to efficiently reduce the spectrum fragmentation in both static network design and dynamic network control scenarios. With novel metrics for channel frequency assignment defined on the grid, the developed scheme was found to substantially relax the complexity inevitable with flexible grid systems and mitigate the fragmentation that occurs during channel capacity upgrades. Numerical evaluations under several network conditions, including different channel bandwidth configurations, network topologies and so on, confirmed that the number of fragments and the number of fibers in a network can be greatly reduced as compared with the conventional flexible grid approach.

A preliminary version of this paper was presented at an international conference [21]. This paper includes more detailed evaluations on several real topologies with different channel bandwidth configurations and insight into the strategy for periodic network expansion scenarios such as channel-frequency-bandwidth assignment and path detouring strategies. It will be shown that the frequency bandwidth of future optical channels should be always minimized as it attains higher frequency utilization efficiency.

2. Preliminaries

2.1 Regular Channel Capacity Upgrade and Network Bandwidth Expansion

We assume fully transparent optical networks, which do not adopt wavelength conversion and regeneration. The frequency assignment follows the flexible grid standardized by ITU-T [4]; the channel center frequency is on a grid with interval of 6.25 GHz and the frequency bandwidth is an integral multiple of 12.5 GHz. Hereafter, the 12.5 GHz width frequency assignment unit is called a frequency slot. Throughout this paper, we regard the words path and channel interchangeable; channel will be used when we focus just on the frequency assignment on a link and path is used when we consider routing and frequency slot assignment. The modulation format is uniquely selected for each channel bitrate; no distance-adaptive modulation/bit-rate selection is assumed. This is because the distance-adaptive modulation format selection necessitates the adaptation to highest possible symbol rate and modulation format among selectable configurations and the distance-adaptive bit-rate selection often obliges to use user-network interfaces in lower bit-rate modes. Moreover, the impact of distance-adaptive modulation/bit-rate selection strongly depends on the size of networks and will make the performance analysis complicated and difficult. Thus, we omit the distance-adaptive modulation format selection in this paper, and hence, frequency bandwidths occupied by the same bitrate channels are uniform. Each optical path occupies the same contiguous frequency slot set from the source to destination nodes.

Periodic network upgrade (ex. every 3–6 months) and the network bandwidth expansion problem are handled in this paper. Some existing channels are replaced with new larger capacity ones or new ones are added at each upgrade. New channels are accommodated by vacant wavelength spaces in a fiber as much as possible, and new fibers will be installed for those channels that could not be accommodated by the vacant spaces. During the expansion, existing active channels must be kept untouched to avoid service disruption. New channels generally occupy broader frequency bandwidths, and hence, severe fragmentation can occur in each fiber. The following discussion is valid for any combination of channel frequency bandwidths; however, we assume that channels of different capacities need different frequency bandwidths to highlight the impact of fragmentation. Moreover, three channel capacities of 100G/400G/1 Tbps are selected not only for notational simplicity, but also they well represent upgrades to channels of different frequency bandwidths. Table 1 shows the number of slots required for these channel capacities. The numbers of slots in Pattern #1, 4/7/15, are mutually co-prime numbers, and could give the worst fragmentation. On the other hand, Pattern #3 is introduced to test if using the multiple slot number structure is advantageous in reducing fragmentation. Pattern #2 stands for an intermediate scenario. Various sets of channel capacities were tested to confirm the effectiveness of the proposed scheme.

Figure 1(a) shows an example of the fragmentation caused by non-uniformity in the channel frequency bandwidth under Pattern #1. Four 400 Gbps channels are upgraded to 1Tbps ones where two of these are replaced at a time. When C and D are upgraded at the next timing to 1Tbps channels, a gap is created between C and A that cannot accommodate a 1Tbps channel. On the other hand, Fig. 1(b) shows the upgrade of four channels under Pattern

Table 1 Number of slots necessary for all channels.

	100Gbps	400Gbps	1Tbps
Pattern #1	4	7 [22,23]	15 [24]
Pattern #2	4	7 [22,23]	16
Pattern #3	4	8	16

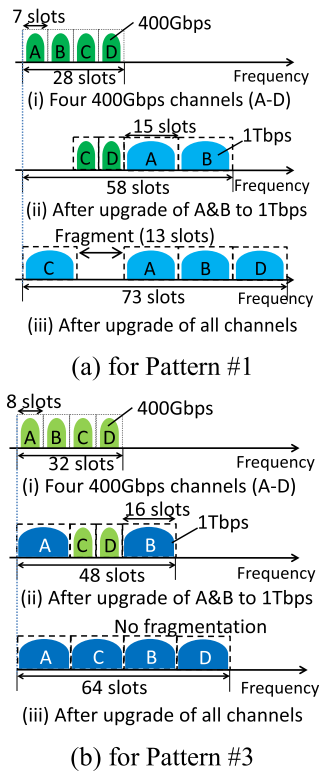


Fig. 1 Channel capacity upgrade and fragmentation.

#3. No fragmentation occurs in this case. This simple example shows that, without an efficient channel upgrade strategy, severe fragmentation could occur, especially when the numbers of slots necessary for a new channel and that for an existing channel are co-prime numbers.

The aim of this paper is to find a channel capacity upgrade and network bandwidth expansion strategy that maximizes fiber frequency utilization efficiency over the network's lifetime: the strategy should be effective regardless of which channel capacity combinations are used.

2.2 Semi-Flexible Grid Optical Path Network

Figure 2 shows examples of channel frequency allocations for 100G/400G/1 Tbps channels on: (a) 100 GHz spacing ITU-T fixed grid, (b) flexible grid, and (c) semi-flexible grid [19], [20]. Channel frequency bandwidths are set to Pattern #1 in Table 1. The semi-flexible grid network uses the same frequency slot granularity as flexible grid networks, but each set of same bitrate channels employs a fixed frequency grid that is fixed specifically to the channel bitrate (and modulation format), and one edge of the grid (the far most left grid in Fig. 2(c)) for each channel speed is anchored at a specific frequency. Please note that this scheme differs from existing mixed line rate systems where a single fixed grid accommodates different line rate channels (for example, using 50 or 100 GHz spacing). The bitrate specific frequency slot width (frequency grid) enables us to use cost-effective tunable lasers and tunable filters (needed for non-coherent

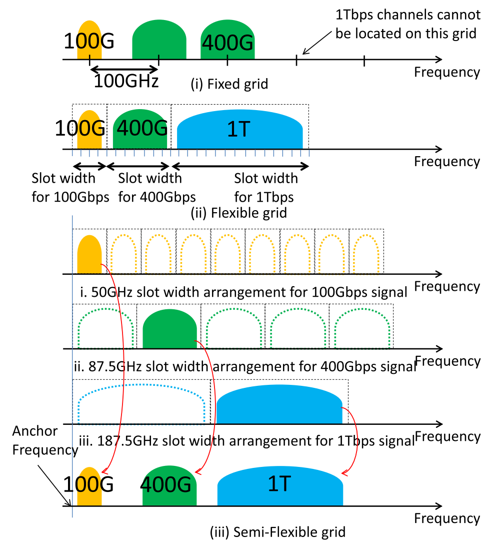


Fig. 2 Fixed/flexible/semi-flexible grids.

detection), the same as those used for fixed grid systems [8]. Extensive numerical experiments on various network topologies under dynamic path control scenarios with various sets of channel bandwidth distributions have elucidated that the semi-flexible grid network scheme almost matches the path accommodation performance of flexible grid networks [19], [20].

3. Proposed Channel Capacity Upgrade and Network Expansion Method

In order to realize better fiber frequency utilization throughout network lifetime, the fragmentation must be suppressed during and after each upgrade (e.g. from 100G to 400G). The suppression after finishing the upgrade to new higher bitrate channels can be achieved by the semi-flexible grid introduced in Sect. 2.2 as it always enforces the alignment of channels. Thus the point is how to suppress the fragmentation during each upgrade where different channel capacities will coexist in the network.

Here we concentrate same bitrate channels into specific frequency ranges. In each range, channels of the same frequency bandwidth (i.e. same bitrate/capacity) will be regularly aligned and densely accommodated on the semi-flex grid. Moreover, given the set of bitrate specific grids, how many higher bitrate channels will be blocked by a newly installed channel is estimated. Considering these requirements, the following two metrics are defined for adding new channels. The first metric minimizes unused slots by grouping the same bandwidth channels and allocating them together as much as possible. The second mitigates the blocking created by future channel installations.

(1) Target frequency: for each channel capacity, select one target frequency. In the routing and frequency slot assignment process for a path, the frequency gap between the target frequency and the selected channel center frequency is used as a cost for the assignment.

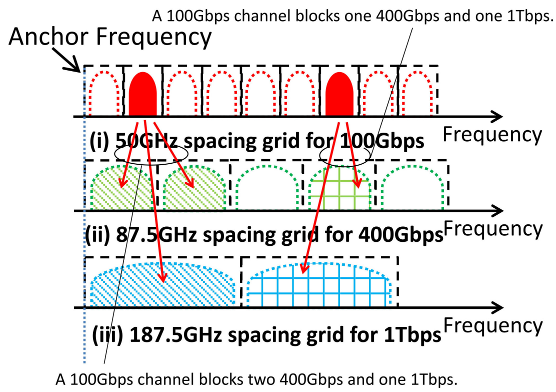


Fig. 3 Blocking of next-generation channels by current channels; 4/7/15 slots for 100G/400G/1 Tbps channels (Pattern #1).

Our preliminary study [19], [20] on semi-flexible grid networks selected the target frequency according to the existence ratio of the channel capacity in the network; the available frequency band (ex. C band and C&L-band) is divided into several blocks so that the block widths are proportional to the existence ratio. Both edge frequencies of the frequency band (ex. C band and C&L-band) are selected for the target frequencies of channels, which correspond to edge blocks. For the remaining blocks, their center frequencies are used as the target frequencies of the corresponding channels. This scheme works well for dynamic path operation scenarios where optical paths are frequently setup and torn down, since it offers fast convergence in channel capacity distribution to the corresponding frequency blocks. However, Sect. 2.1 posits the network expansion characterized by incremental optical path upgrades. The capacity distribution of paths to be newly established will not match that of existing paths, which were established according to prior distributions. Therefore, we need a different target frequency selection strategy that can accelerate the convergence of capacity distribution for the network.

This paper proposes an alternating target frequency selection scheme such that the two edge frequencies are selected in turn. In actual network upgrades, up to 2–3 generations of channels will coexist in a network; dominant, growing, and declining generations. Based on this assumption, the target frequency of the first generation channel is set to one of the edges of the frequency band, the target frequency of the second generation channel is set to the other edge, the third generation is set to the first frequency, and the fourth generation is set to the second frequency alternately. At each upgrade timing, declining generation channels are replaced by growing generation channels as a common target frequency is assigned to both generations.

(2) Future channel blocking: in the slot assignment process for a new path, the number of channels potentially blocked by future generations in new path installations is estimated and taken to be a cost (See Fig. 3).

We assume that channel generations/capacities are labeled $c = 1, 2, 3 \ldots$ (ex. $c = 1$: first generation channels). Let the set of grid frequencies and the bandwidths for channel capacity c be $G_c = \{g_{(c,1)}, g_{(c,2)} \ldots\}$ and b_c, respectively. Then the number of next generation channels blocked by accommodating a c th generation channel in $g_{(c,n)}$ will be given by $\#\{g_{(c+1,k)} \mid \left(g_{(c,n)} - \frac{b_c}{2}, g_{(c,n)} + \frac{b_c}{2}\right)$ and $\left(g_{(c+1,k)} - \frac{b_{c+1}}{2}, g_{(c+1,k)} + \frac{b_{c+1}}{2}\right)$ do overlap$\}$, where $[a, b]$ stands for the closed interval from a to b and # is the cardinality of the given set. We adopt the weighted sum of the number of blocked channels of next and future generations (i.e. $c+1, c+2, \ldots$) as a metric for frequency assignment and call it future channel blocking. In the following, the number of frequency slots necessary for a channel of that generation is commonly used for weighting. However, the other schemes that use more general weighting can be applied.

The proposed design and expansion algorithm for semi-flexible grid networks with the above metrics is shown below.

⟨Semi-flexible Grid Network Design and Periodic Network Expansion⟩

<u>Step 0. Parameter Setup</u>

Define allowable hop count increment h_slug≥0 for detours (i.e. hop slug) from the shortest hop route. Use the k-shortest algorithm to find a route candidate set R(s,d) for each node pair (s,d) that satisfies the hop slug limitation. Select target frequencies for all channel capacities/generations alternately.

<u>Step 1. Initial network design</u>

For a given set of initial path connection requests, sort the requests in descending order of hop counts from shortest routes between source and destinations. If there are multiple requests with the same hop counts, sort these requests in descending order of their number of slots. If there are multiple paths whose order cannot not determined, set their order randomly. For each request with a source and destination node pair (s,d), find all vacant grid positions for the request on all routes in R(s,d). Among the vacant grid positions, select the one minimizing the future channel blocking metric. If multiple positions minimize the metric, the difference to corresponding target frequency is used for the selection. If multiple positions on different routes minimize the difference, select the one on the shorter route. Establish the path for the request on the selected route with the grid position. Repeat until all paths are established.

<u>Step 2. Network expansion</u>

At each scheduled expansion timing, install upgraded paths according to given upgrade requests. Establish new paths according to path addition requests. Finally, tear down old paths for all upgrade requests. Go back to Step 1.

Remark.

i. The hop slug parameter, h_slug in Step 0, was introduced to control path detours. Detouring may contribute to reducing the number of fibers when the path is established; however, the penalty caused by the use of a longer route will generally degrade the network resource utilization efficiency in later expansion timings. We have verified the impact of different hop slug values and our result implies that h_slug = 0 will be the best for almost all cases.

ii. Step.2 of the above algorithm establishes new paths and then existing paths to be upgraded are removed so that service disruption will be avoided in any case. If a path is filled with low priority services which accept disruption, the path could be torn down at first and the released frequency slots can be occupied by new paths.

4. Numerical Experiments

4.1 Simulation Setup

We assume that the available frequency range is the C-band (4,400 GHz wide) holding 352 frequency slots (12.5 GHz). The channel capacities and numbers of slots in Table 1 are assumed. Physical network topologies tested were 5 × 5 regular mesh network, USNET [25], Cost266 Pan-European network [26], and Japanese 25 node network [27]. Their numbers of nodes and bidirectional links are (25,40), (26,51), (25,43), and (24,43), respectively (See Fig. 4). The hop slug parameter is set to h_slug=0.

The traffic growth ratio is set to +30%/year. Green-field design is conducted to find initial networks and then 40 upgrades are done, once every 3 months over 10 years (or 40 times); the final traffic volume increase is 1.3^{10}=13.8 times. The number of each capacity/generation channels in a network is determined to match the traffic volume and the ratio at each expansion timing. Two different upgrade scenarios are assumed (see Figs. 5(a) and 5(b)); the first one represents slow upgrade and the second one fast upgrade. These are used to investigate whether the difference in upgrade speed affects fragmentation. The benchmarking alternative is the conventional flexible grid network approach using first-fit routing; the frequency slot assignment method also adopts the target frequency metric. All results in this section are the averages of 10 trials.

4.2 Simulation Results

1) Evaluation of impact by proposed metrics
For the proposed method, four variants are assumed to verify the impact of metrics; with semi-flexible grid (S), with semi-flexible grid and target frequency (S&T), with semi-flexible grid and weighting by potential channel blocking (S&W), and with all three metrics (S&T&W). The difference between proposed (S) and conventional is only the grids adopted; semi-flexible and flexible ones. The assumed numbers of necessary frequency slots for 100G/400G/1Tbps channels are 4/7/15; i.e. Pattern #1.

Figures 6 and 7 show the variations in necessary number of fibers in networks normalized by those necessary for the conventional alternatives for the 5 × 5 regular mesh and USNET. The semi-flexible grid successfully reduces the number of fibers necessary over the lifetime, especially when one bitrate channel is dominant. The weighting considering potential channel blocking also suppresses the number of fibers; this effect becomes clear in situations where multiple different bitrate channels coexist. This observation elucidates the importance of optimization considering not only the current route and frequency slot assignment but also possible future assignments. The impact of the target frequency is rather limited, however some improvement is observed. For both scenarios, proposed method with all metrics gives better results. For slow scenarios, about 10% fiber reduction at the end of the period is observed. For fast scenarios, about 15% fiber reduction at the end of the period is observed. Figure 8 shows the results for the proposed method with all metrics on the four topologies. Almost the same results were obtained regardless of topologies; this is because the number of nodes in a network will be up to several tens due to the limitation in transparent transmissible distance/hops and degrees of nodes will be less than 10 for real topologies. Therefore,

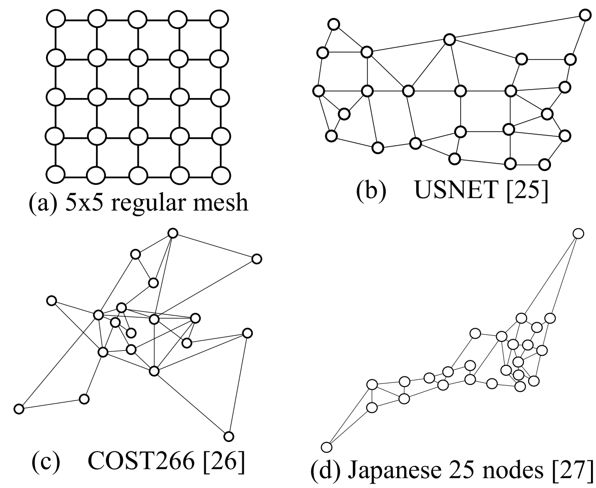


Fig. 4 Topologies.

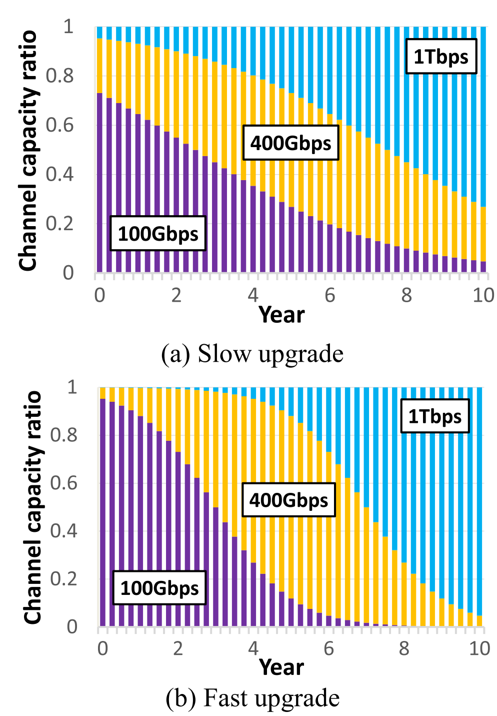
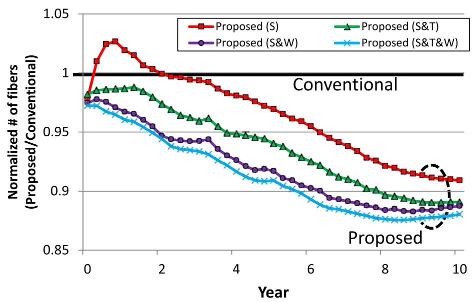
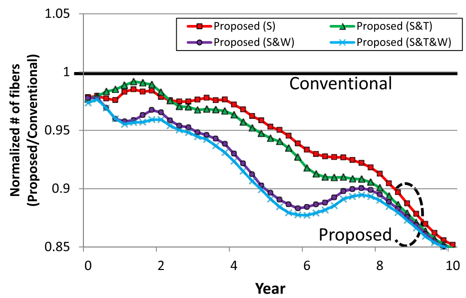


Fig. 5 Variations of channel capacity ratio.

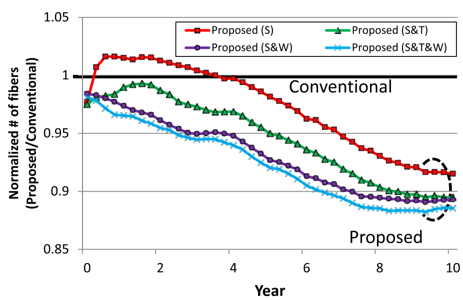


(a) Slow upgrade

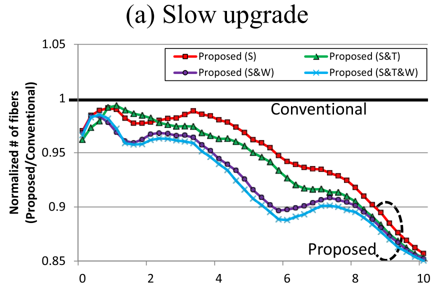


(b) Fast upgrade

Fig. 6 Variation of number of fibers normalized by conventional on 5 × 5 regular mesh.

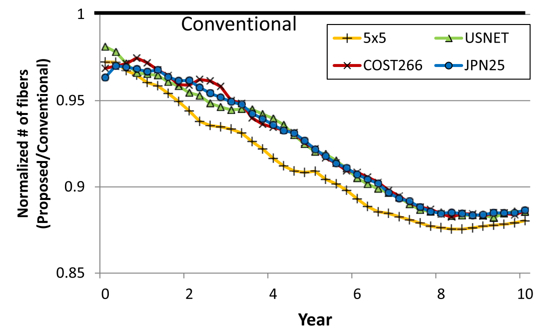


(a) Slow upgrade

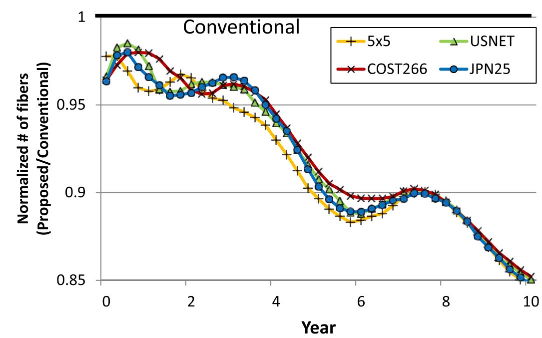


(b) Fast upgrade

Fig. 7 Variation of number of fibers normalized by conventional on USNET.



(a) Slow upgrade



(b) Fast upgrade

Fig. 8 Variation of numbers of fibers on all topologies.

the proposed method would be valid for different types of core networks.

2) Fragment mitigation by semi-flexible grid

The previous part showed that the semi-flexible grid offers a substantial fiber number reduction. The reduction ratio is maximized when 1Tbps channels are dominant. We show how the fragmentation mitigation by the semi-flexible grid contributes to this.

Frequency slots that are not occupied by any channel are classed as either usable or fragmented. Suppose there are consecutive unused slots in the frequency domain. If the number of the slots is sufficient to accommodate a 1Tbps channel, all are classed usable. Other unused slots are called fragmented. Some fragmented are still usable for 100G and 400G channels which occupy less number of slots. From here we use the results using all metrics as the proposed method (S&T&W). Pattern #1 of Table 1 is commonly used in this part.

Figures 9 and 10 show the variations of fragmentations on USNET where the results are normalized by the number of frequency slots in fibers necessary for conventional method. The fragmentations are well suppressed by the introduction of the proposed method and the fragmentation suppression contributes the reduction of fibers shown in Fig. 7. Moreover, the ratio of usable slots for the proposed is rather high than that for the conventional. Figure 11 shows, for USNET, the relationship between the number of occupied slots and that of fibers. A lower bound is derived by dividing the number of occupied slots in all fibers by the number of slots in a fiber. The proposed method keeps the gap to a lower bound small throughout the network expansions; the gap is almost constant for the slow upgrade case. Thus even if we try to mitigate fragmentation at each network expansion with some de-fragmentation technique, the room for fiber number reduction is quite limited. On the other hand, the conventional approach yields wide gaps for the first few expansions due to severe fragmentation as shown in Figs. 9(a) and 10(b). These results elucidate that the proposed method not only reduces the number of fibers but also encourages

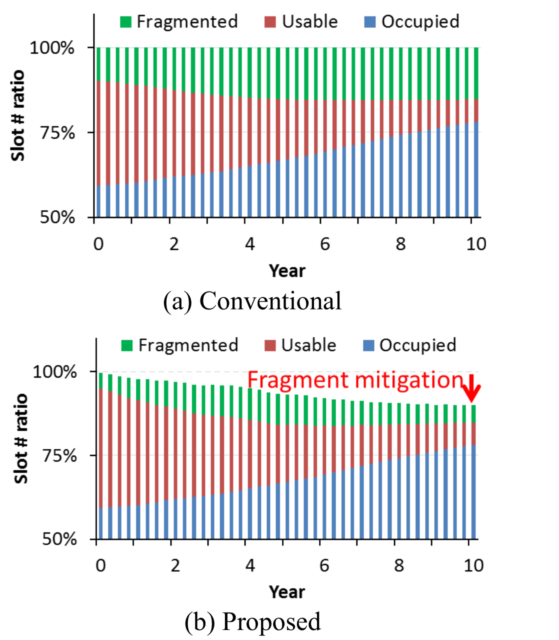


Fig. 9 Breakdown of frequency slot classes on USNET under slow upgrade.

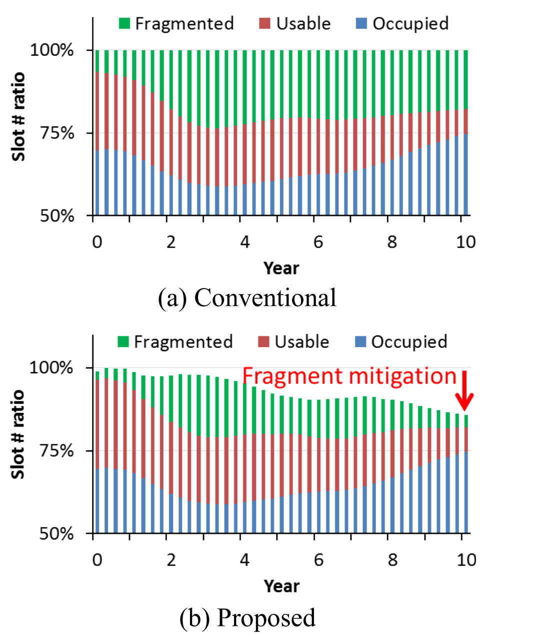


Fig. 10 Breakdown of frequency slot classes on USNET under fast upgrade.

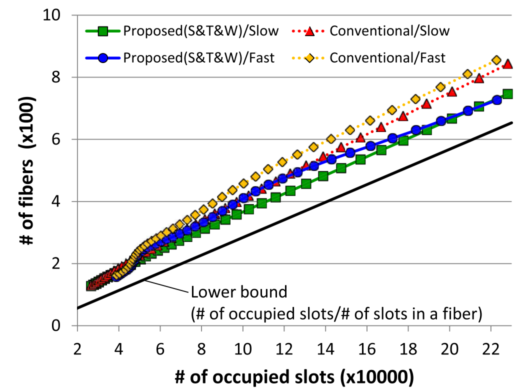


Fig. 11 Variations of numbers of fibers subject to numbers of occupied slots on USNET.

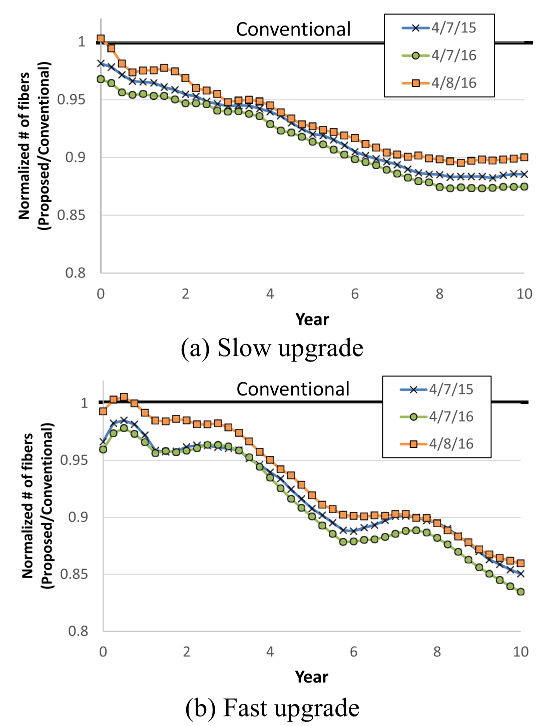


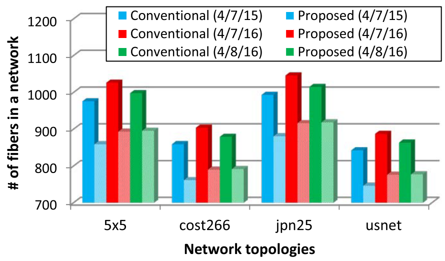
Fig. 12 Variation in number of fibers normalized by corresponding conventional on USNET.

the efficient utilization of installed fibers.

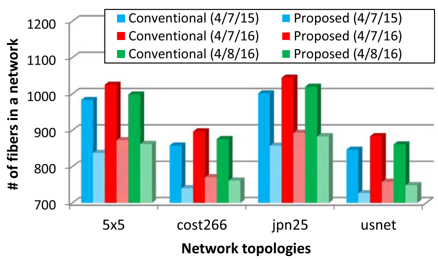
3) Impact by slot pattern selection

In this part, we verify the difference in channel accommodation efficiency among 3 slot patterns of 4/7/15, 4/7/16, 4/8/16; i.e. Patterns #1, #2, and #3 in Table 1. Figure 12 shows the variations in the number of fibers in networks normalized by conventional alternatives in each slot pattern on USNET. Figure 13 shows the numbers of fibers after all expansions in all topologies were completed. By using the proposed method for both scenarios, numbers of fibers are well suppressed throughout all expansions for all slot patterns and all topologies.

Figure 14 shows the ratios of the fiber numbers normalized by the conventional alternative with Pattern #1. The results show that Pattern #1 gives the minimum fiber number for both conventional and proposed. The numbers of fragmented slots normalized by the conventional alternative with Pattern #1 are shown in Fig. 15. Proposed schemes substantially reduce the fragmentation for all patterns. Pattern #3 gives the minimum fragmentation both for conventional and proposed; however, this channel accommodation efficiency of the multiple slot number structure of Pattern #3 is not advantageous in reducing the total fiber number. This result

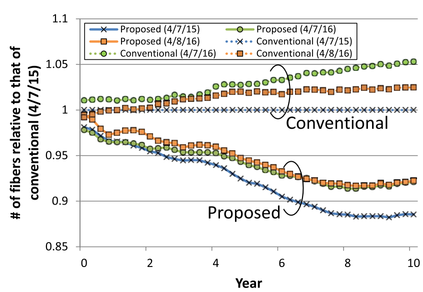


(a) Slow upgrade

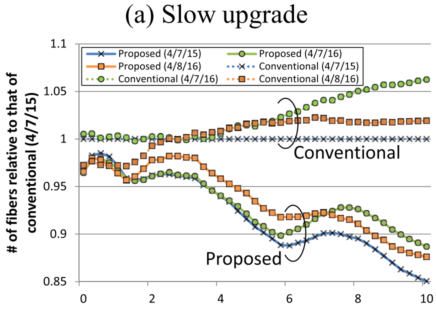


(b) Fast upgrade

Fig. 13 Numbers of fibers after all expansions for all topologies.



(a) Slow upgrade

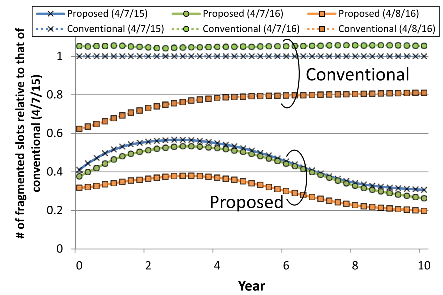


(b) Fast upgrade

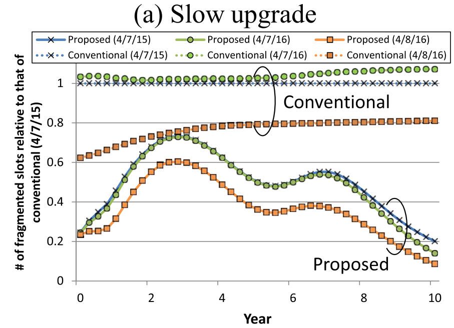
Fig. 14 Variation in number of fibers normalized by conventional for Pattern #1 on USNET.

indicates that it is better to set each channel to the minimum number of slots rather than using the multiple slot number structure.

All the results in Sect. 4.2 1)–3) prove that smooth upgrade to future broad bandwidth channels is done incrementally by the proposed method, regardless of the number of frequency slots occupied by each future channel, scenario, and topology.



(a) Slow upgrade



(b) Fast upgrade

Fig. 15 Variation in number of fragmented slots normalized by conventional for Pattern #1 on USNET.

5. Conclusion

We introduced an efficient network upgrade and expansion method that can make the most of the next generation channel capacity and thus accommodate further increases in traffic. While excessive fragments are generated in the conventional flexible grid configuration during disruption-free upgrade processes, our proposed combination of the semi-flexible grid and two cost metrics establishes some regularity, minimizes disturbance in the upgrade process, and effectively reduces the number of fragments and fibers. As a result of extensive investigations such as two upgrade scenarios, combination of number of slots, some topologies, etc., the proposal attains good results in all situations, which confirms the robustness of the proposed method. They also indicated that even though the regular multiple slot number structure, such as 50G/100G/200 GHz, will reduce the fragmentation of frequency slot assignment, the frequency bandwidth of future optical channels should be always minimized as it attains higher frequency utilization efficiency regardless of the penalty caused by the fragmentation.

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