Migration from Fixed Grid to Flexible Grid in Optical Networks

Xiaosong Yu, Massimo Tornatore, Ming Xia, Jianping Wang, Jiawei Zhang, Yongli Zhao, Jie Zhang, and Biswanath Mukherjee

ABSTRACT

Optical WDM backbone networks based on fixed spectrum grid have limitations such as low spectrum utilization and rigidity in provisioning for heterogeneous rates. Flexible-grid technologies can alleviate these limitations for on-demand provisioning. These technologies represent promising candidates for future optical networks supporting beyond-100-Gb/s signals. However, a one-time green-field deployment of flexible-grid technologies may not be practical, as the already-made investment in existing fixed-grid WDM networks needs to be preserved, and interruptions to ongoing services need to be minimized. Therefore, we envision that fixed- and flexible-grid technologies will coexist, which will bring the challenge of interoperating fixed- and flexible-grid equipment. It is also important to design the optimum migration strategy to maximize cost effectiveness and minimize service interruption. In this article, we discuss the key aspects of network architectures supporting coexistence of fixed and flexible grid technologies, and outline the challenges of network operations. We also propose and evaluate different migration strategies from fixed grid to flexible grid under different network scenarios.

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INTRODUCTION

The vision of 50 billion connected devices by 2020 is constantly pushing the traffic volume carried by our networks to new heights. Although wavelength-division multiplexing (WDM) technology has already provided high bandwidth using parallel wavelength channels, the overall network spectrum efficiency is severely discounted by the fixed grid definition and standard rate transmission (e.g., 10 Gb/s and 40 Gb/s). Recently, the concept of flexible grid has been introduced into optical transport networks [1–3]. The flexible grid technology evolves the traditional International Telecommunication Union (ITU) grid toward high flexibility with fine-grained spectrum slots (e.g., 12.5 GHz vs. 50 GHz or 100 GHz) [4]. Advanced optical transmission technologies, such as coherent optical orthogonal frequency-division multiplexing (OFDM) [5], Nyquist WDM (N-WDM) [6], and optical arbitrary waveform generation (OAWG) [7] are identified as the enabling technologies for flexible-grid optical networks. By using on-demand spectrum assignment and adaptive modulation formats, flexible grid can significantly improve the spectrum efficiency and increase the overall network capacity [8]. In addition, super channels (i.e., channels spanning multiple slots) can be set up to support high-bandwidth demands (e.g., 400 Gb/s and 1 Tb/s [2]).

In light of these advantages, a flexible-grid network is regarded as a promising candidate for future transport infrastructure. In [9], various migration options from fixed grid to flexible grid are investigated, and the impacts on flexibility and cost are discussed. In [10], the authors review the main drivers during the migration toward flexible grid, and introduce a planning tool to optimize the migration process. However, they leave an open but important question: how should the fixed-grid network be migrated toward the flexible grid? In other words, the problem of devising the most effective migration path toward flexible grid is still underinvestigated. Our recent work addresses the static routing and spectrum allocation (RSA) problem in fixed- and flexible-grid networks, and proposes several migration strategies with the goal of reducing the bandwidth blocking ratio of the network [11, 12]. This article investigates this problem in more detail (with a special focus on quantifying how much benefit we can get by gradually migrating from the current fixed grid to the flexible grid), and compares the performance of several migration strategies under different traffic profiles.

The remainder of this article is organized as follows. We discuss the network architecture with coexisting fixed-grid and flexible-grid nodes, and study the lightpath routing and spectrum allocation problem. We discuss how to perform effective and gradual migration from fixed grid to flexible grid. A case study is provided to compare the performance of the migration strategies. We then conclude the article.

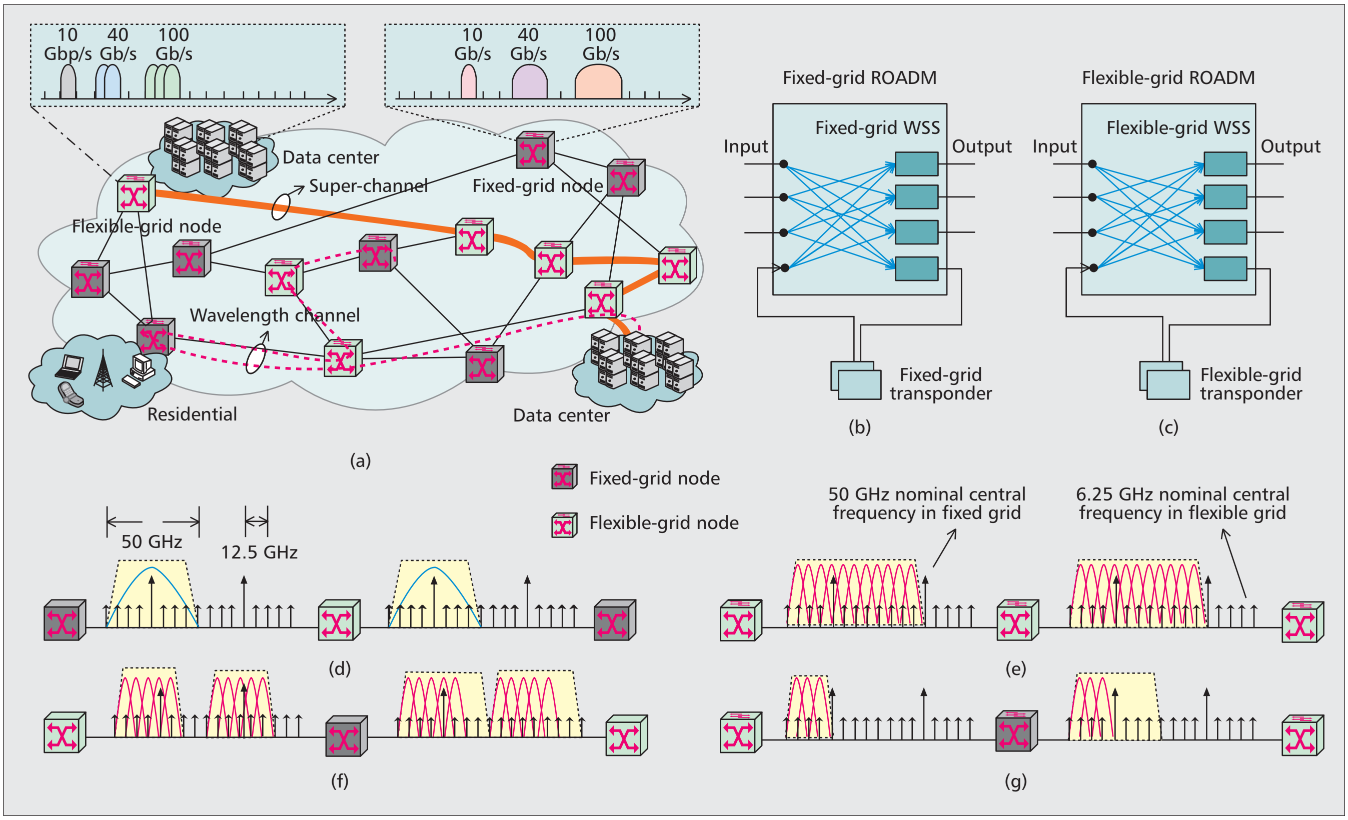


Figure 1. Optical network with co-existing fixed-grid and flexible-grid technologies: a) network architecture; b) fixed-grid ROADM; c) flexible-grid ROADM; d) wavelength channel; e) 200-Gb/s super-channel; f) two 100-Gb/s channels; g) 40-Gb/s subchannel.

Brown-Field Migration

Due to the increasing pressure on network operators to provide higher bandwidth with more efficient resource utilization, replacing the legacy fixed-grid equipment with flexible-grid equipment in their transport networks is just a matter of time. However, the operator's decision to migrate to flexible-grid technology will be influenced by key factors such as trade-off between benefit and equipment cost, compatibility with legacy systems, and complexity of network management. On one hand, the key enabling equipment (e.g., bandwidth variable wavelength-selective switches [BV-WSSs] supporting different grid definitions) has not yet reached a price point that allows massive deployment. It may not be economically viable to make a one-time complete upgrade to full flexible-grid technology for the entire network. On the other hand, before the current optical transport network capacity is exhausted, the current fixed-grid network could be kept maximally operational during the migration to preserve the already-made investment.

Network Architecture

In practice, a likely scenario is that traffic loads on some nodes/links are significantly higher than others, so they become bottlenecks [10]. For example, a common scenario concerns nodes associated with data centers, which tend to generate a large amount of traffic and can benefit from high-bandwidth super-channels interconnecting them. In these situations, the equipment causing the bottleneck could be replaced with flexible-grid equipment. As a result, brownfield flexible-grid deployment on top of the existing fixed-grid network could happen as shown in Fig. 1a.

While the sparse deployment of flexible-grid nodes can cost-effectively increase the capacity of only selected nodes/links, one challenge we will face is in the operational issues due to the coexistence of fixed-grid and flexible-grid technologies. Fixed- and flexible-grid nodes require different technologies. In particular, reconfigurable optical add/drop multiplexers (ROADM) are the key equipment to perform wavelength switching at intermediate nodes. Fixed-grid ROADMs follow the traditional rigid ITU-Telecommunication Standardization Sector (ITU-T)-defined central frequencies and spectrum grids (e.g., 50 or 100 GHz) regardless of the actual bit rate carried by each individual channel. Network devices (e.g., optical switches, multiplexers, and transponders) have to comply with this grid, as shown in Fig. 1b. The flexible-grid ROADM is different, as shown in Fig. 1c. Embedded wavelength-selective switches (WSSs) in flexible-grid ROADM do not need to strictly follow the ITU-T fixed grid, and can switch multiple concatenated slices as a single entity, where each slice may be 6.25 or 12.5 GHz.

These fixed-grid and flexible-grid nodes would need to interoperate before all nodes are upgraded to flexible grid. So a question is: how can newly added flexible-grid nodes be operated

Nodes generating the largest number of low-bandwidth traffic (e.g., 40 Gb/s) will be upgraded first. The intuition for this strategy lies in the fact that flexible-grid technology is spectrum-efficient for low-bandwidth traffic due to its on-demand spectrum provisioning instead of the rigid provisioning in fixed-grid technology.

in a network with other legacy fixed-grid nodes? Below, we discuss the relevant challenges in terms of lightpath routing, wavelength assignment, and spectrum allocation.

Interoperation between Fixed-Grid and Flexible-Grid Nodes

When a request arrives, we need to establish an optical path between its source and destination by determining a route through the network, and assigning/allocating a wavelength/frequency slot for this path. Here, a frequency slot is a spectrum allocation dedicated to a certain connection, and is specified by its nominal central frequency and slot width. Suppose a route is selected for a lightpath in an optical network with both fixed-grid and flexible-grid technologies, so there are several situations for wavelength assignment (WA)/spectrum allocation (SA):

- When the source is a fixed-grid node, we have the traditional WA problem. If the traffic demand is larger than 100 Gb/s, it can be served by several lightpaths, each accommodating 100 Gb/s or less (all following the same path, if possible).
- When the source is a flexible-grid node, there are two cases:
  - If the nodes on the path are flexible nodes, we have the SA problem, where a single-carrier channel or a super-channel with multiple subcarriers can be set up to accommodate the demands.
  - If there are both fixed- and flexible-grid nodes on the path, the spectrum is shared as common resources between fixed- and flexible-grid technologies, and the corresponding WA and SA problem becomes complex, different from WA in fixed grid and SA in flexible grid. On the path from the flexible-grid node to the fixed-grid node, we have the SA problem; but from the fixed-grid node to the flexible-grid node, we have the WA problem. If the traffic demand is larger than 100 Gb/s, we set up several lightpaths, each offering up to 100 Gb/s rate.

Figures 1d–1g illustrate four possible cases in networks with fixed-/flexible-grid coexistence. We consider the spectral granularity of fixed-grid nodes to be 50 GHz and that of flexible-grid nodes to be 12.5 GHz. Figure 1d shows the spectrum utilization of links for a 100-Gb/s lightpath that originates from a fixed-grid node and goes through a flexible-grid node. It occupies 50 GHz on both a fixed-grid link (i.e., a link originating from a fixed-grid node) and a flexible-grid link (i.e., a link originating from a flexible-grid node); Fig. 1e shows a 200-Gb/s lightpath that originates from a flexible-grid node and then goes through a flexible-grid node. Since we can set up a super-channel that comprises six 12.5 GHz slots, only 75 GHz of spectrum will be used instead of two 50 GHz channels in a fixed-grid network. However, when the path of a 200 Gb/s demand originates from a flexible-grid node but goes through a fixed-grid node, as shown in Fig. 1f, two lightpaths are set up, with each offering up to 100 Gb/s. Figure 1g shows a 40-Gb/s lightpath originating from a flexible-grid node and going through a fixed-grid node. Here, 25 GHz spectrum will be assigned to the optical path on the flexible-grid link, and 50 GHz will be assigned on the fixed-grid link, since the switching granularity of the fixed node cannot be smaller than 50 GHz.

Migration Strategies

As discussed in the previous section, migration to flexible-grid technologies may not be done at one time; instead, a network operator may choose to first upgrade network equipment where a bottleneck occurs. Around this scheme, various interesting questions arise as discussed below.

Question 1: Which node should be upgraded first?

When choosing a node (or nodes) to upgrade, many factors should be considered, such as network topology, traffic profile, network load, and network bottlenecks. Following are the strategies considered in our study, which are numerically evaluated in the next section.

Highest degree first (HDF): Nodes with the highest node degree will be chosen first to be upgraded. High node connectivity may have a positive impact on the upgrade performance, as a node with a higher degree connects to a larger number of other nodes in the network, thereby facilitating traffic provisioning options.

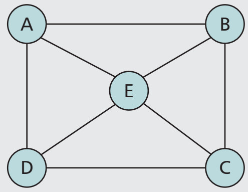
Highest generated traffic first (HGTF): Nodes that generate more traffic will be upgraded first so that more traffic might benefit from the upgrade.

Highest carried traffic first (HCTF): Nodes that carry the most traffic will be upgraded first. This is similar to the previous case, but it also considers transit traffic. Here, transit traffic includes all generated traffic as well as pass-through traffic.

Most high bandwidth traffic first (MHTF): Nodes generating the largest amount of high-bandwidth traffic (e.g., 400 Gb/s or 1 Tb/s) will be upgraded first. The argument for this strategy is that flexible-grid nodes enable super-channels for high-bandwidth requests, thus saving spectrum resources.

Most low bandwidth traffic first (MLTF): Nodes generating the largest number of low-bandwidth traffic (e.g., 40 Gb/s) will be upgraded first. The intuition for this strategy lies in the fact that flexible-grid technology is spectrum-efficient for low-bandwidth traffic due to its on-demand spectrum provisioning instead of rigid provisioning in fixed-grid technology. For example, a flexible-grid node uses only 25 GHz spectrum resources instead of 50 GHz to transmit a 40 Gb/s signal, which saves spectrum resources.

Figures 2a–2c illustrate the above migration strategies. Figure 2a shows a small five-node topology, with the traffic matrix shown in Fig. 2b. Total carried traffic by each node is shown in Fig. 2c. Thus, for HDF, node E will be upgraded first, since it has the largest node degree (i.e., 4); for HGTF, node D will be chosen, since it generates the highest traffic load (i.e., 500 Gb/s in total); for HCTF, node B will be chosen, since it



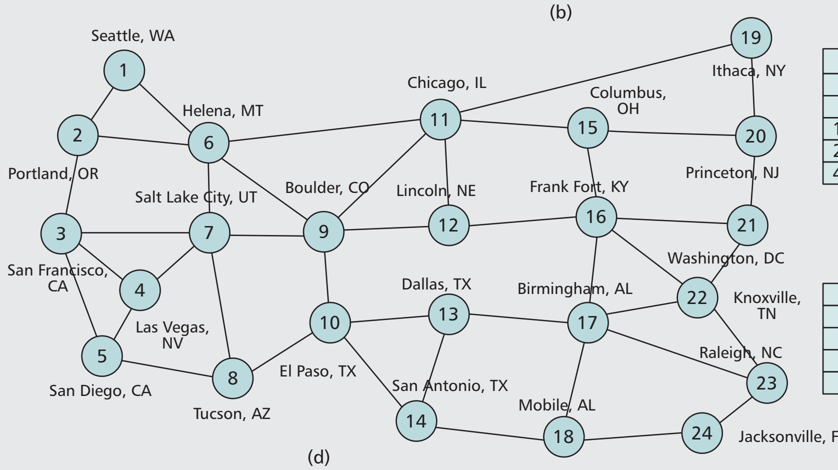
(a)

Source	Destination	Bit rate (Gbps)	Route
A	B	40	A-B
	E	40	A-E
	C	200	A-B-C
D	E	100	D-E
	B	400	D-C-B

(b)

Node	Carried traffic (Gbps)
A	280
B	640
C	600
D	500
E	140

(c)



(d)

	Fixed grid		Flexible grid	
Channel	Spectrum	#wavelength	Spectrum	# slots
40 Gbps	50 GHz	1	25 GHz	2
100 Gbps	50 GHz	1	37.5GHz	3
200 Gbps	100 GHz	2	75 GHz	6
400 Gbps	200 GHz	4	125 GHz	10

(e)

	Profile 1	Profile 2	Profile 3
40 Gbps	50%	20%	0%
100 Gbps	30%	50%	40%
200 Gbps	15%	20%	40%
400 Gbps	5%	10%	20%

(f)

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Traffic distribution	63	60	83	60	134	3	19	52	10	67	272	27	124	138	81	3	21	20	3	3	63	18	42	84

(g)

Figure 2. a) 5-node topology; b) traffic matrix; c) carried traffic by each node; d) U.S. network topology; e) optical channels in fixed-grid and flexible-grid technologies; f) connection demand ratios in different traffic profiles; g) traffic distribution in the non-uniform case.

carries the highest traffic (i.e., 640 Gb/s); for MHTF, node D will be chosen, since it generates the largest number of high-bandwidth traffic demands (400 Gb/s); for MLTF, node A will be chosen, since it generates the largest number of low-bandwidth traffic demands (40 Gb/s).

Question 2: Should we create "flexible island(s)"?

If we simply follow the above policies, we would upgrade the nodes one by one, without considering the influence of the already upgraded nodes. For example, if we upgrade a node with a neighbor that is already a flexible-grid node, a high-bandwidth and spectrum-efficient super-channel can be set up between them. Thus, we can state that these two flexible-grid nodes have formed a "flexible-grid island." More rigorously, an island is a subset of network nodes where any two nodes of the subset can be connected to each other directly or through the node(s) that is (are) also in the same subset; a flexible-grid island means every node in this subset supports flexible-grid technology. In general, trying to form an island during a gradual migration process seems to be an effective way to maximize carried traffic, and some possible considerations can be drawn if we want to create flexible-grid islands.

Enlarging a single island. In this case, we could start by upgrading the first node according to, say, HCTF, and then choose as the second node the one with the highest carried traffic, but only among nodes adjacent to those already upgraded. This policy leads to the formation of an island that will keep growing during the migration until a complete migration is done.

Enlarging multiple islands. Since a traffic pattern in the network may have several centers (e.g., the east and west coasts of the United States may be observed with higher traffic volume than other places), a further improvement would be to have multiple islands growing independently. An idea is to choose nodes to be upgraded using metrics that can capture the *locality of traffic*.

Different migration strategies can also be devised if an operator decides to upgrade more than one node at a time. More optimized approaches could be explored to identify the most efficient migration strategy when the number of nodes upgraded at each step can be more than one.

Question 3: How many nodes should be upgraded?

While the ultimate goal is to migrate the entire network to support flexible-grid technology, upgrading only a subset of the nodes might be enough to remove current network bottlenecks. This may lead to different numbers of

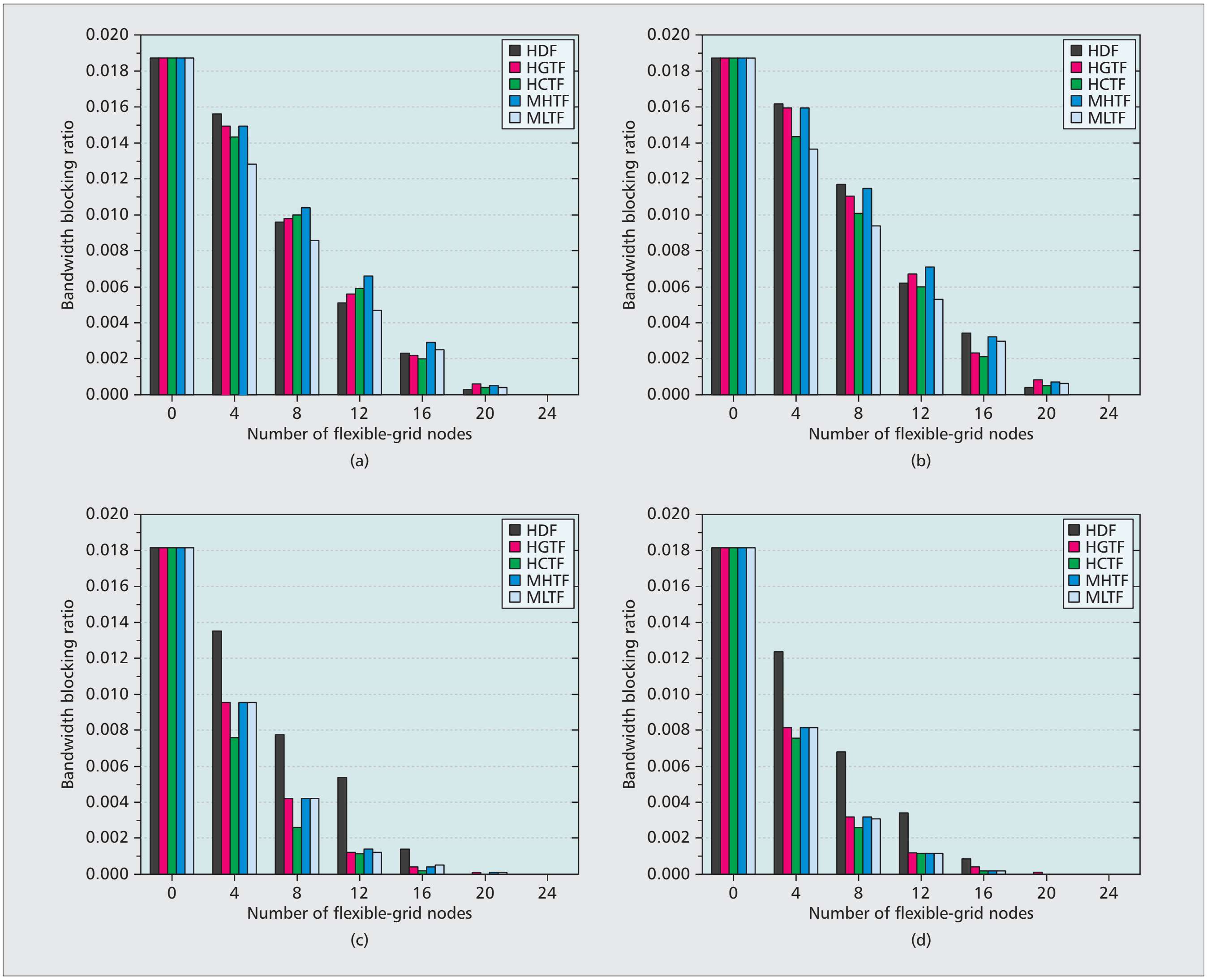


Figure 3. Bandwidth blocking ratio for traffic profile 1: a) forming one island under uniform traffic; b) forming two islands under uniform traffic; c) forming one island under non-uniform traffic; d) forming two islands under non-uniform traffic.

nodes to be upgraded under a given scenario with a predetermined objective (e.g., to lower bandwidth blocking probability under some predefined target). Also, for a network planning scenario, the number of upgraded nodes has an important effect on the node selection decision. For example, in Fig. 2a, when only two nodes are upgraded, nodes A and B may be selected; it may be the case that nodes A, C, and E need to be upgraded when the quota is three.

CASE STUDY

We compare the migration strategies described earlier on a 24-node U.S.-wide network shown in Fig. 2d. Each link is bidirectional with 4 THz spectrum in each direction. For the fixed-grid technology, we consider a 50 GHz frequency grid, so each link has 80 wavelengths; for flexible-grid technology, the frequency grid is 12.5 GHz, so each link has 320 frequency slots. We generate 500,000 any-pair connection demands following Poisson arrival, and their bandwidth requirements are uniformly chosen among [40, 100, 200, 400] Gb/s. We use Fig. 2e to map a bandwidth demand to a spectrum allocation using fixed-grid and flexible-grid technologies, respectively. We use dual-polarization quadrature phase-shift keying (DP-QPSK) for 40 and 100 Gb/s rates in both the fixed-grid and flexible-grid scenarios, while we use orthogonal frequency-division multiplexing (OFDM) version of DP-QPSK for 200 and 400 Gb/s in the flexible-grid scenario. Here, we suppose the guard band is included in the required spectrum, and the maximum optical reaches for DP-QPSK and OFDM-DP-QPSK are 2800 km and 3500 km [13], respectively. Connection requests are handled sequentially; and for each connection, k-shortest path routing (with $k = 5$) and first-fit spectrum assignment are used. For a flexible-grid lightpath, if there are not enough spectrum resources to set up a super-channel, we also try to split the high-bandwidth request into small lightpaths [14]. For example, one 400 Gb/s connection can be split into two 200 Gb/s channels or four 100 Gb/s channels.

Since traffic may influence the migration strategies, we consider three traffic profiles as shown in Fig. 2f. For example, in *profile 1*, the

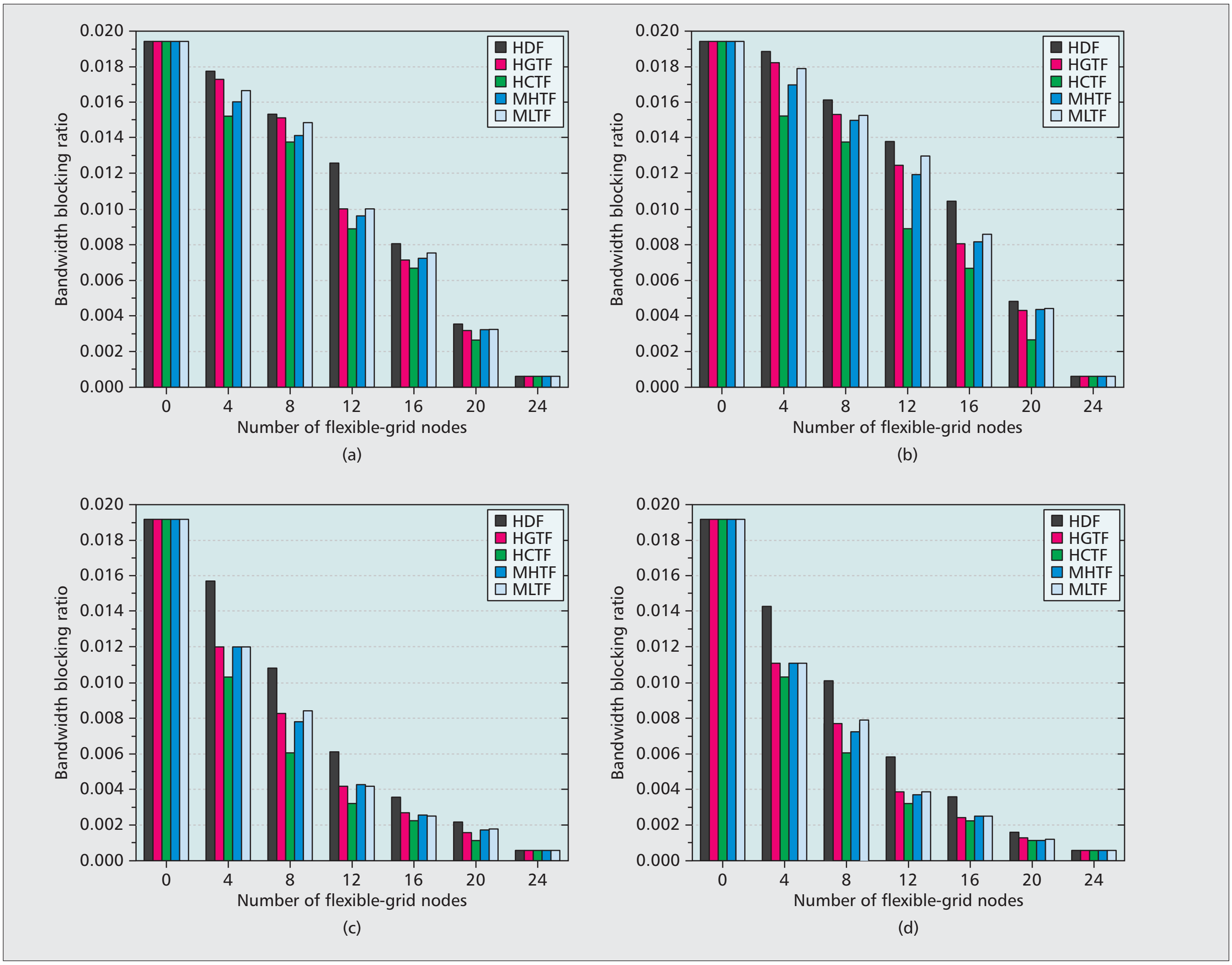


Figure 4. Bandwidth blocking ratio for traffic profile 2: a) forming one island under uniform traffic; b) forming two islands under uniform traffic; c) forming one island under non-uniform traffic; and d) forming two islands under non-uniform traffic.

ratios of 40, 100, 200, and 400 Gb/s are 50, 30, 15, and 5 percent, respectively (i.e., low-bandwidth traffic is predominant); while in *profile 2*, 100 Gb/s traffic is predominant, with only 20 percent 40 Gb/s traffic; in *profile 3*, all the traffic are 100G and beyond, with 400 Gb/s traffic as high as 40 percent. Please refer to Fig. 2f for the values of these ratios in all traffic profiles. The migration strategies are applied on all three profiles. For each profile, traffic can be either uniformly or non-uniformly distributed among all the nodes. For the second case, our study assumes that traffic is distributed according to the population of the city at the corresponding node as shown in Fig. 2g. Strategies' performances in terms of bandwidth blocking ratio (BBR), that is, the rejected bandwidth over the total bandwidth, are compared. The reason for using BBR is that for a network with non-uniform bandwidth requests, BBR is a weighted metric showing the capability of the network to admit traffic volume rather than only number of requests.

For *traffic profile 1*, the BBR for the different migration strategies is shown in Figs. 3a and 3b for uniformly distributed traffic, and Figs. 3c and 3d for non-uniformly distributed traffic. The traffic load is set to 900 Erlang. From Fig. 3a we see that as the number of upgraded nodes increases, the BBR of all the migration strategies decreases. When we upgrade fewer than 12 nodes, MLTF gives the best performance whether we form one or two islands. The reason is that in profile 1, the percentage of 40 Gb/s traffic is 50 percent, and if we choose the node that has the most 40 Gb/s demands to upgrade, more benefit can be achieved. However, if we upgrade more than 12 nodes, HCTF gives better performance. If we compare the performance of forming one island in Fig. 3a and two islands in Fig. 3b, we find that the BBR of HCTF is always the same. The reason is that, using HCTF, the updating sequence of the nodes for the one-island or two-island cases is the same. For other strategies, forming one island is better than forming two islands. This is due to the fact that in uniform traffic, there is not much difference in traffic intensity in the network, so forming one island brings more benefit than forming two islands. For non-uniform traffic, BBR drops more rapidly, as shown in Figs. 3c and 3d. For example, when we upgrade four nodes (forming

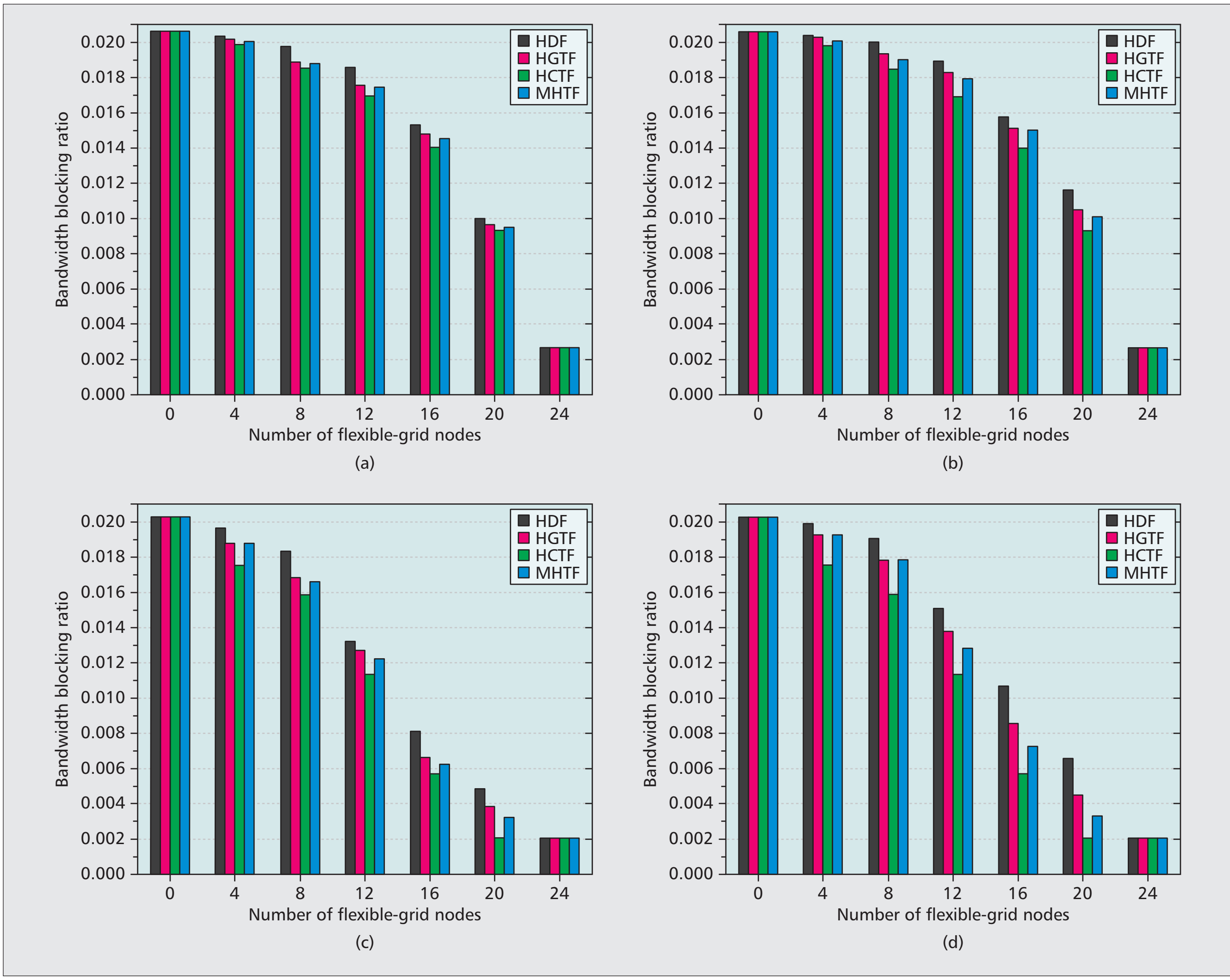


Figure 5. Bandwidth blocking ratio for traffic profile 3: a) forming one island under uniform traffic; b) forming two islands under uniform traffic; c) forming one island under non-uniform traffic; and d) forming two islands under non-uniform traffic.

one island) under uniform traffic distribution by HCTF, the BBR is reduced by only 17.6 percent; while under non-uniform traffic, it can be reduced by up to 55.6 percent. The reason is that in the non-uniform case, traffic is unevenly distributed, and by choosing a small number of nodes with the most traffic, the BBR can be reduced quickly. In addition, HCTF always gives the best performance whether forming one or two islands. Different from uniform traffic, BBR is lower if we form two islands for other migration strategies, as shown in Fig. 3d.

Figures 4a–4d show the BBR of different migration strategies for *traffic profile 2*. Figures 4a and 4b are for uniform traffic, and Figs. 4c and 4d are for non-uniform traffic. In order to have similar BBR values to profile 1, the traffic load is decreased to 760 Erlang. From Fig. 4a, we can see that HCTF gives the lowest BBR no matter how many nodes are upgraded. By comparing Figs. 4a and 4b, we find that the performance of HCTF is the same with one or two islands. The reason is that when using HCTF, the updating sequence of the nodes for the one-island and two-island cases is still the same. For other strategies, forming one island is more efficient than forming two islands, confirming that for uniform traffic, the one-island strategy is better. For non-uniform traffic, as seen before, the BBR again decreases more rapidly than in the uniform case. For example, by upgrading only four nodes, the BBR of HCTF can be reduced by up to 47 percent under non-uniform traffic instead of only 21 percent in the uniform case. In addition, in the non-uniform case, HCTF again gives the same performance when forming one or two islands, but now for other strategies, forming two islands gives a lower BBR compared to forming only one island, which confirms the trend in Figs. 3c and 3d.

Figures 5a–5d show the BBR of different migration strategies for *traffic profile 3*. Figures 5a and 5b are for uniform traffic, and Figs. 5c and 5d are for non-uniform traffic. Also, in this case, to have similar BBR values to profiles 1 and 2, we decrease the traffic load to 580 Erlang. From Figs. 5a and 5b, we see that under uniform traffic, all migration policies achieve comparable performance, with HCTF a little better. For non-uniform traffic in Figs. 5c and 5d, we see that if we upgrade only a small portion of nodes to flexible grid, less benefit is obtained com-

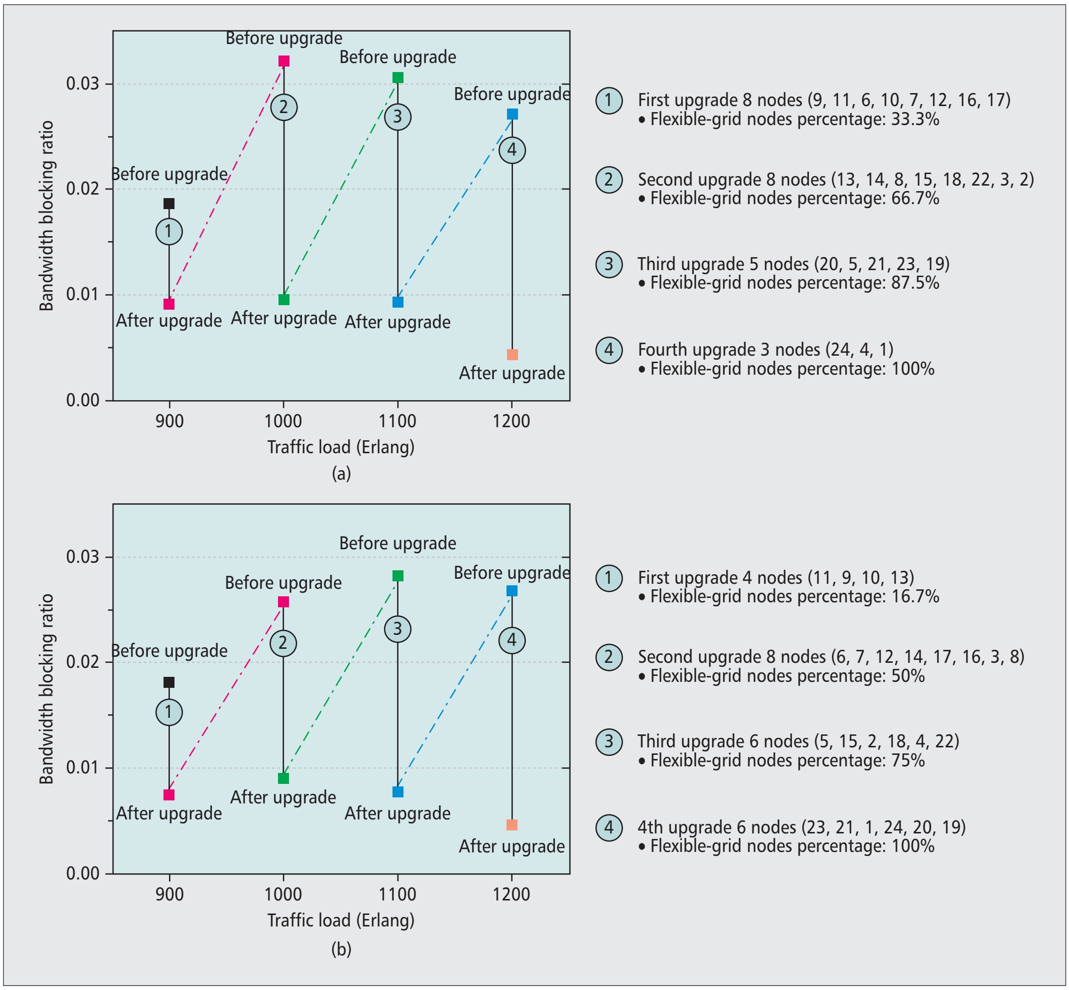


Figure 6. Network's gradual migration to flexible-grid technology: a) uniform traffic; b) non-uniform traffic.

A general conclusion is that migrating to flexible-grid technology can improve network capacity and lead to lower BBR. This benefit can be achieved even if we only upgrade a small portion of the network to flexible grid, especially for non-uniform traffic.

pared to profiles 1 and 2. For example, if four nodes are upgraded (i.e., 17 percent of the total nodes), BBR is reduced by only 10 percent. Only if we upgrade to 12 nodes (i.e., 50 percent of total nodes) can we reduce the BBR by up to 45 percent. The reason is that in profile 3, the percentage of 200 Gb/s and 400 Gb/s traffic (i.e., requests served by super-channels) is much higher than in profiles 1 and 2, so the network needs a much larger number of flexible nodes to avoid blocking these super-channels, and cannot quickly benefit by upgrading only a small proportion of nodes. By comparing Figs. 5c and 5d, we see that forming one island is better than forming two islands, which is different from profiles 1 and 2.

Finally, to investigate the benefits of gradual migration, we consider scenarios with increasing traffic volume. As an example, we consider traffic profile 1 and the HCTF migration strategy, and the results are shown in Figs. 6a and 6b. Our objective is to keep BBR less than a threshold (1 percent in this study). First, we consider uniform traffic. In our initial setting, traffic load is 900 Erlang and the BBR of the network is 1.87 percent, which is higher than 1 percent. This means the network should be upgraded. We start to upgrade the nodes one by one. After upgrading eight nodes (i.e., nodes 9, 11, 6, 10, 7, 16, 12, and 17), BBR is reduced to 0.91 percent. Since the BBR is now lower than the 1 percent performance target, we stop the upgrade process. But as traffic load increases to 1000 Erlang, the BBR increases to 3.23 percent, which means another upgrade process is needed. An additional eight nodes (i.e., nodes 13, 14, 8, 15, 18, 22, 3, and 2) are selected to be upgraded such that the BBR decreases to 0.97 percent. As traffic load increases to 1100 Erlang, BBR increases to 3.05 percent, and triggers another upgrade operation. Now, we upgrade another five nodes (i.e., nodes 20, 5, 21, 23, and 19) and BBR drops to 0.92 percent. When the traffic loads increases to 1200 Erlang, the BBR increases to 2.7 percent, triggering another upgrade operation. After upgrading the rest of the nodes in the network (i.e., nodes 24, 4, and 1), the BBR drops to 0.43 percent, which meets our objective again. When traffic increases to 1300 Erlang, the BBR reaches 1.76 percent, and we would need additional nodes/links or other traffic/network engineering (TE/NE) approaches to satisfy the 1 percent BBR objective since all the nodes in the network have already been upgraded. Note that for non-uniform traffic (Fig. 6b), considering the same settings, the sets of nodes upgraded for the different traffic loads are {11, 9, 10, 13}; {6, 7, 12, 14, 17, 16, 3, 8}; {5, 15, 2, 18, 4, 22}; and {23, We found that the migration strategies should be carefully chosen by considering traffic profiles and traffic distributions. Network operators can benefit from gradually upgrading their network to flexible grid, especially when traffic is non-uniformly distributed in the network.

21, 1, 24, 20, 19}, respectively. Also, when traffic load is 1300 Erlang, the network needs to deploy additional resources or use other TE/NE strategies to achieve the BBR objective. This example indicates that the network can benefit from gradual migration to flexible grid, especially under non-uniform traffic.

From the case study, we see that the performance of a migration strategy depends partly on the traffic profile. For example, if low-bandwidth demands (e.g., 40 Gb/s) are dominant, MLTF may give better performance if only a few nodes are upgraded; but if high-bandwidth demands (e.g., 400 Gb/s) are dominant, HCTF may perform better no matter how many nodes are upgraded. Also, traffic distribution has an important effect on the performance of a migration strategy. For example, under uniform traffic, forming one flexible-grid island gives more benefit; however, under non-uniform traffic, forming more than one island is a better choice. A general conclusion is that migrating to flexible-grid technology can improve network capacity and lead to lower BBR. This benefit can be achieved even if we only upgrade a small portion of the network to flexible grid, especially for non-uniform traffic.

Conclusion

Compared to fixed-grid technology, flexible-grid technology has many advantages such as higher capacity, more flexibility, and better spectrum efficiency, which make it a promising candidate for future optical transport networks. This article investigates various strategies for migrating from fixed grid to flexible grid, and studies the problem of interoperation between fixed-grid and flexible-grid technologies. Migration strategies from fixed grid to flexible grid are discussed, with their performance compared in a number of case studies. From the results, we find that the migration strategies should be carefully chosen by considering traffic profiles and traffic distributions. Network operators can benefit from gradually upgrading their network to flexible grid, especially when traffic is non-uniformly distributed in the network.

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