Minimizing Spectrum Wastage in Optical Mesh Network by In-network Superchanneling

Masahiro Nakagawa, Takeshi Seki, Rie Hayashi, Toshihiko Tamura
Network Service Systems Laboratories
NTT, Inc.
3-9-11, Midori-cho, Musashino-shi, Tokyo, 180-8585, Japan
mshr.nakagawa@ntt.com

***Abstract*—Emerging IoT and AI-related applications are driving the need for optical network evolution such as available capacity. However, since the C-band capacity is rapidly approaching the theoretical limit, conventional solutions based on advanced modulation technologies are no longer sustainable. These trends necessitate rethinking how spectrum resources are utilized in optical path routing. In this paper, we propose superchannel adapters that leverage state-of-the-art wavelength conversion to minimize spectrum wastage. Our solution can effectively reduce the total amount of guard bands to be wasted, which allows more traffic demands to be accommodated within limited network resources. Numerical experiments using our tailored provisioning scheme verify that more than 30% of capacity expansion can be achieved without upgrading the fiber infrastructure.**

Keywords*—superchannel routing, wavelength conversion, optical node configuration, path provisioning, spectrum wastage

I. Introduction

Due to rapid growth in IoT- and AI-related applications, network connectivity has become increasingly important. In addition, cyber-physical systems (CPS) and forthcoming 6G (Beyond 5G) use cases will impact network requirements [1]–[4]. Real-time data to and from sensors and actuators must be efficiently handled in a CPS-enabled 6G society. Moreover, the number of devices connected to the network continuously increases and data sources (i.e., communication endpoints) will be distributed throughout the network. Advanced latency/jitter-sensitive use cases require an exceptional end-to-end communication environment. These trends impose stringent pressure on optical networks and further evolution is required in terms of the available capacity and/or the number of connections that can be accommodated.

Significant progress in optical networks has been achieved mainly by increasing per-channel capacity so far; however, such an approach is becoming unsustainable because of the theoretical limit [5], [6]. In particular, there are several design tradeoffs to be considered in optical network systems. For instance, higher-order modulation formats enable more bits per symbol, which results in higher per-channel capacity at the cost of reduced optical reach. Moreover, if baud rate is increased, the required bandwidth (spectrum resource) is also increased, which can decrease the number of channels that can be provided. Therefore, to further increase capacity and/or the number of connections achieved with particular spectrum resources (e.g., 4.8 THz in the C-band), spectrum wastage must be minimized.

In today's optical networks, actual spectrum utilization is limited by not only the wavelength/spectrum-continuity constraint but also the guard bands between optical channels. In fact, guard bands are typically placed between every channel to minimize filtering penalties induced by optical nodes [7], [8]. This means a considerable amount of spectrum is wasted, which is a strong motivation for revisiting superchannel routing. Note that the superchannel concept allows multiple channels to be closely spaced and routed together as a single entity, which has been widely discussed in the paradigm of elastic optical networking [9]–[11]. In the literature, there have been various transmission experiments [12]–[14], and resource assignment problems in superchannel-enabled networks have been addressed [15]. However, most conventional studies focused on "end-to-end" transmission where all (sub)channels are generated and received at a common source and destination, respectively. While they have been based on the original concept of superchannel, its benefit can be obtained only when large traffic demands between a certain node pair are handled all together. Furthermore, when data sources and optical transceivers are distributed throughout the network, and/or when accommodating demands in an incremental manner, network operators cannot enjoy the benefit of superchannels. Hence, a novel solution is required by extending the original concept, which enables dense packing of multiple channels in the spectrum domain at arbitrary nodes, including intermediate nodes on the route.

In this paper, we propose the superchannel adapter (SChA) that allows for significant guard-band suppression, which leads to network capacity expansion. Specifically, we present our SChA-based solution and a configuration example within optical nodes, in which state-of-the-art wavelength conversion technology is leveraged. The key novelties of this work are that superchannels can be set up between arbitrary nodes as logical tunnels and that wavelength conversion is utilized to reduce the amount of guard bands. A tailored path provisioning scheme and differentiation from existing work are also presented. Numerical results reveal that our solution is effective in spectrum saving, which can increase the number of connection requests that can be accommodated by more than 30% using the existing fiber infrastructure.

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II. IN-NETWORK SUPERCHANNELING ENABLED BY SUPERCHANNEL ADAPTERS

In this section, we propose the SChA and introduce our solution that utilizes superchannel routing in addition to traditional wavelength routing. The aim of the SChA is to densely arrange multiple channels for suppressing the total amount of guard bands wasted in fiber links. In particular, SChAs have functions to arrange incoming channels and combine them with local add channels to form a densely packed superchannel. Naturally, SChAs should also have functions to separate local drop traffic from a superchannel and rearrange the remaining channels for forwarding at wavelength granularity. For such (re)arrangement operations in the spectrum domain, we apply wavelength conversion [16], [17]. Although wavelength conversion itself has been studied for many years, it should be emphasized here that significant progress has recently been reported. In [18], an energy-efficient and low-latency wavelength converter (WC) has been presented and experimentally demonstrated. Such an advanced WC is the key component to implement SChAs.

We illustrate the principle of our solution in Fig. 1, where a superchannel is available as a virtual tunnel between nodes #7 and #8. In other words, a path can benefit from superchannel routing even between intermediate nodes. This superchannel directly connects a pair of nodes that employ SChA, and add/drop operations are allowed only at the edge nodes. In an example depicted in Fig. 1, three paths (A, B, and C) utilize superchannel routing from node #7 to node #8, where guard bands between adjacent channels are reduced compared to traditional wavelength routing. Moreover, a broader filter bandwidth is configured for such a superchannel as multiple channels are routed together. This can cope with dense packing in the spectrum domain while mitigating filtering penalties. As a result, more capacity can be offered without significantly affecting transmission quality.

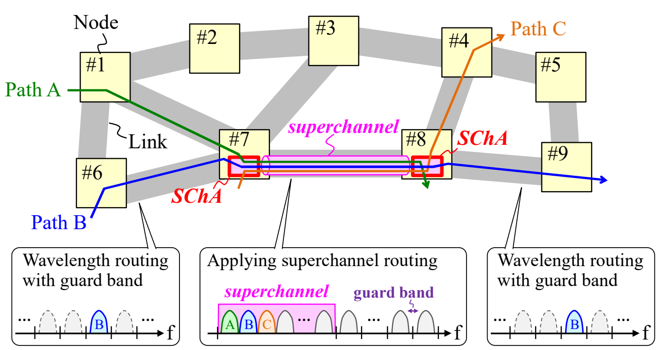


Fig. 1. Optical network utilizing superchannel adapters.

A configuration example of optical nodes employing the SChA is presented in Fig. 2, where two nodes (representing nodes #7 and #8 in Fig. 1) are depicted and three arrows denote data flow of paths A, B, and C in Fig. 1. In this configuration, a route-and-select type multi-degree reconfigurable optical add/drop multiplexer (ROADM) is assumed. WCs are deployed between the add and drop modules for achieving SChA functionalities. Such add/drop modules are assumed to be filterless. As a WC can change the center wavelength of an optical channel, each channel can be adjusted in the spectrum domain. Naturally, the conversion flexibility (relationship and/or constraint between inputs and outputs) of WCs is an important parameter for our solution. In this paper, we assume optical-analog-optical (OAO) type WCs (presented in [14]) are utilized in the configuration.

The OAO type WC achieves any-to-any wavelength conversion (it can convert any input wavelength to an arbitrary output), which maximizes the degree of freedom in utilizing superchannels and minimizes spectrum wastage. Note that such flexibility allows each channel to use the same wavelength outside a superchannel (in Figs. 1 and 2, the egress-side SChA in node #8 rearranges spectrum of path B back to its original position in the spectrum domain). This allows treating superchannels as virtual tunnels and can prevent an increase in wavelength management complexity. On the other hand, if we allow different wavelengths for transmitter and receiver ends, ingress/egress WCs for add/drop traffic can be omitted as illustrated in Fig. 2. Such omissions can significantly reduce hardware volume for implementing SChAs, which leads to cost-effective solutions.

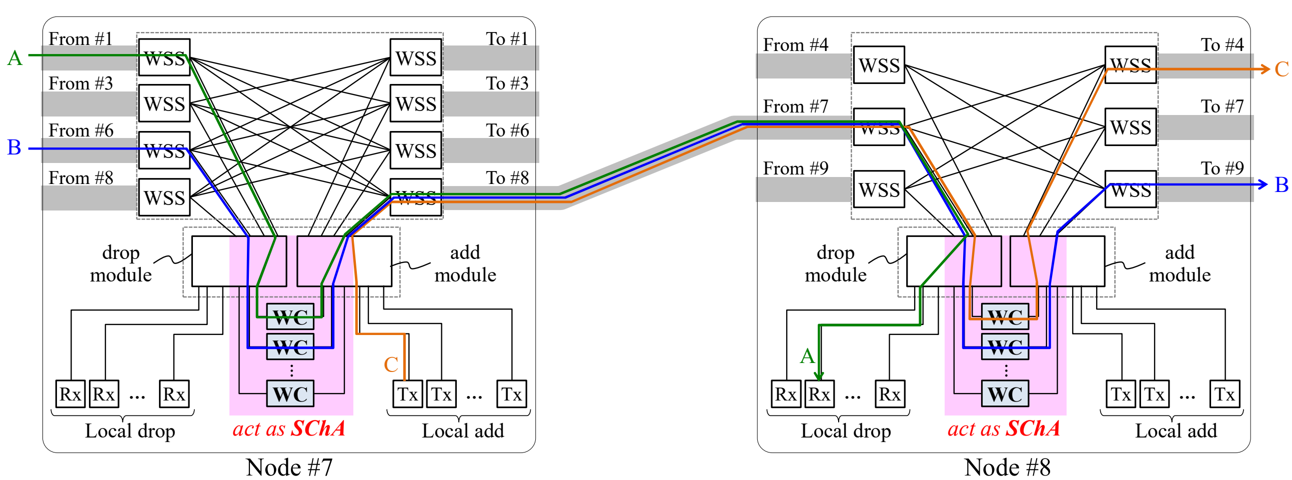


Fig. 2. Example of an optical node configuration employing a superchannel adapter.

III. Path Provisioning Scheme Considering Superchannel Adapters

This section presents a heuristic path provisioning scheme that explicitly considers SChAs and superchannel routing for efficiently handling incremental traffic demands. Note that although all traffic demands are known in advance in the well-known static design scenario, an incremental scenario forces network operators to sequentially accommodate traffic demands by provisioning paths one by one [17]. In this context, superchannel resources must be well managed considering utilization ratios and guard bands between superchannels.

In the related literature, a seminal work on resource assignment with "path grouping" has been reported [19], in which multiple paths can be bundled into a group (an entity similar to a superchannel). However, the work in [19] has focused on minimizing the spectrum narrowing effect when densely packing, and a fixed-capacity group (i.e., the number of paths that can be bundled is predetermined) has been assumed. Such a fixed-capacity strategy causes degradation in spectrum utilization depending on the traffic distribution and connection request arrival pattern. Therefore, in our scheme, superchannels are treated not as fixed-capacity pipes but as virtual tunnels whose capacity can be adaptively adjusted according to traffic patterns. Our scheme consists of two phases and each is summarized as follows.

Phase 1. Soft allocation of superchannel

Before actual traffic accommodation, the SChA deployment is determined and spectrum resources on the superchannel route are reserved. Moreover, which links (more precisely, which sets of links) should utilize a superchannel and how much spectrum should be reserved are determined. Although they can be decided in an arbitrary manner (based on practical knowledge and/or operators' preference), we give a simple method based on congestion estimation. In particular, the traffic distribution or ratio among all node pairs is estimated first and a "weight" is calculated for all links and sets of adjacent links based on the ratio and traffic flow. Note that such a weight equals the sum of the traffic ratios of node pairs whose routes traverse an intended link(s). Next, in descending order of the product of the weight and the hop count, links or link sets are selected, up to a predetermined number. Then, spectrum resources on link(s) are reserved for each superchannel considering the calculated weight values.

Phase 2. Resource assignment with adaptive superchannel adjustment

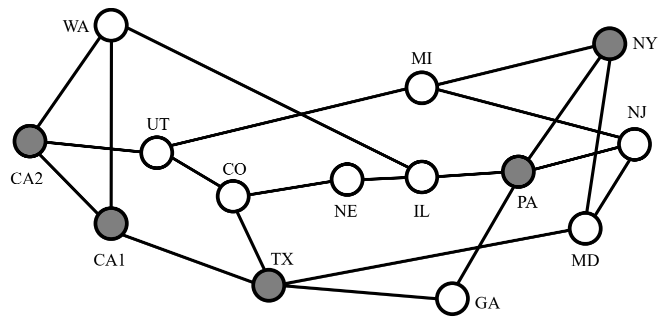
In response to a connection request, a path is established considering superchannels set up in Phase 1, which is executed as follows. First, the fixed shortest route is used to guarantee low latency by avoiding detours. Then, if the route traverses at least one of the superchannels, spectrum assignment computations are executed for each segment outside and inside the superchannel. For outside segments, the first-fit algorithm is applied to densely pack the spectrum. For a segment inside a superchannel, the available resources are searched from the center for later adjustment operations. If available resources are found for all segments and if the reach constraint is satisfied, a path is set up and the request is accommodated. On the other hand, if there is no spare capacity in a superchannel, a capacity (spectrum border) adjustment is attempted, and assignment is retried. Note that if the reach constraint is not satisfied, the assignment is retried without using superchannels. If these retries fail or no available resources are found, the request is blocked.

IV. Numerical Experiments

To numerically investigate the benefits of our SchA-based solution, we conduct realistic simulations using a custom-built discrete-event simulator. In the following, we first describe the assumed network model. Second, we verify the benefits of our in-network superchanneling solution. Then, the impact of the channel spacing within superchannels on network performance is assessed to better understand the characteristics of the proposed solution and to reveal the maximum potential benefits. Moreover, required hardware volume is also discussed to explore the feasibility of our solution.

A. Network Model

The topologies used are NSFNET [20] and JPN12 [21] shown in Fig. 3, where gray-colored nodes represent top five nodes by population. The NSFNET has 14 nodes and 21 bidirectional links, where average link length is 1080 km. On the other hand, the JPN12 has 12 nodes and 17 bidirectional links, where average link length is 437 km. Each node is assumed to be capable of switching operations with 12.5-GHz granularity. Each link is assumed to be a pair of standard single-mode fibers



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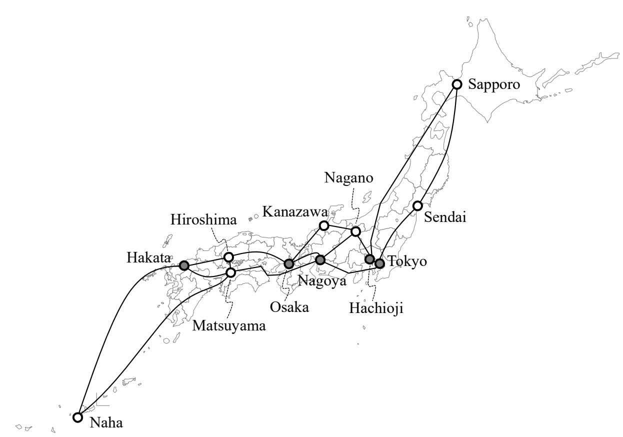

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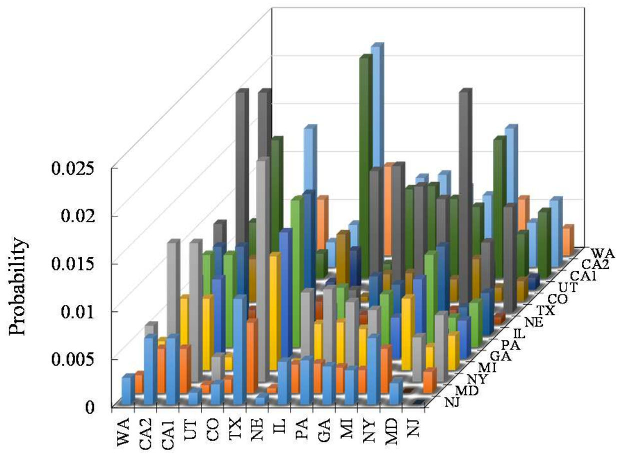
Fig. 3. Network topologies used in numerical experiments.



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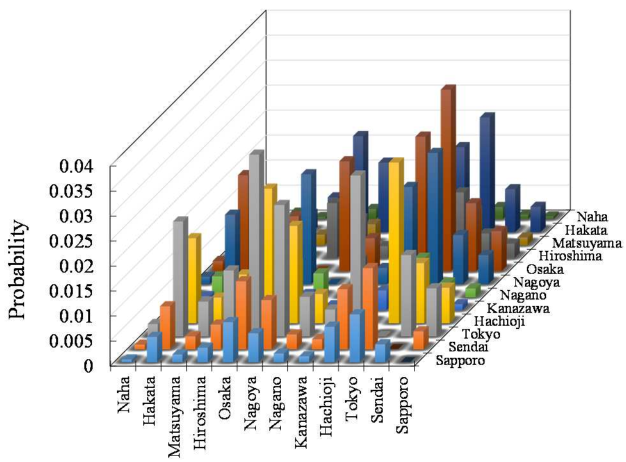

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Fig. 4. Population-based traffic distribution.

with an available bandwidth of 4.8 THz (i.e., C-band). Our simulations assume that a network operator provides end-to-end paths in an incremental manner, in response to connection requests from customers. Such requests are assumed to arrive sequentially and to have a fixed capacity of 100 Gb/s. Moreover, each request has an infinite holding time, i.e., traffic churn or path teardown operations are not considered. Note that request arrival follows a population-based distribution, where the source/destination pair of each request is selected according to population-weighted probability. In particular, such a probability value is defined based on the product of the population at each node, just as in [22]. Such a probability distribution in each topology tested is shown in Fig. 4. Furthermore, 32-Gbaud DP-QPSK is assumed to provide 100-Gb/s paths. The assumed reaches without and with wavelength conversion in SChA are summarized in Table 1, according to the recent work [18].

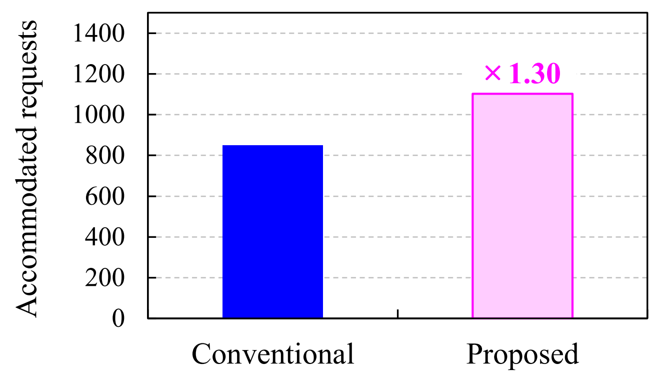
B. *Impact of In-network Superchanneling on Network Performance*

We assess the network capacity by measuring the number of connection requests that can be accommodated before the first blocking occurs. The results (each obtained by averaging 10000 simulation runs) are shown in Fig. 5, where comparisons are provided between the proposed solution and a conventional wavelength-routed solution. Note that the conventional one is a reference scenario, in which individual channels/paths are routed end-to-end with 50-GHz spacing. This channel spacing can suppress the filtering penalty induced by optical nodes at the cost of a relatively large guard band. In this scenario, the well-known shortest path routing and first-fit wavelength assignment algorithm are used and no wavelength conversion is employed. On the other hand, in the proposed solution, 37.5 GHz of channel spacing is applied in superchannels, which is compliant with the flex-grid specifications [23]. In this paper, the number of superchannel pairs to be set up is three, considering a tradeoff between the achievable capacity gain and additional hardware volume.

TABLE I. MAXIMUM REACH AS A FUNCTION OF THE NUMBER OF WAVELENGTH CONVERSIONS

Number of Conversions	Reach
0	5700 km
2	4100 km
4	3100 km
6	2300 km

The results in Fig. 5 reveal that our proposed solution can significantly enhance network performance, enabling the number of accommodated requests to increase by more than 30% compared to the conventional one in both topologies.



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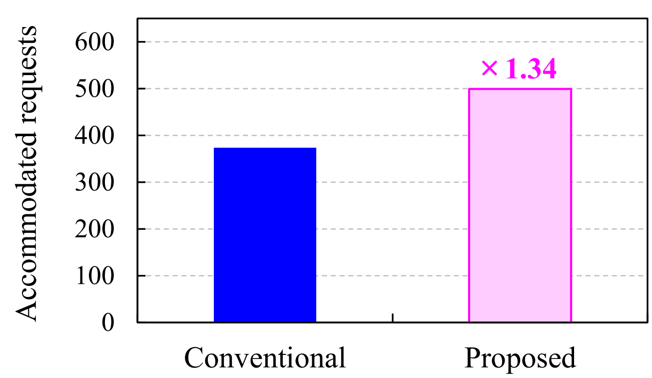

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Fig. 5. The number of connection requests that can be accommodated.

Although the degree of improvement depends on superchannel utilization strategy and/or traffic distribution, it is clarified that three pairs of superchannels enable at least 30% improvement in network capacity in the tested conditions. This improvement is mainly because our solution can save spare spectrum for later requests by reducing the amount of guard bands. It should be noted that the optimal superchannel setting can effectively suppress the required guard bands to be wasted, especially in congested links, which delays the first blocking occurrence. Such delays allow network operators to reduce the frequency of network upgrades that may require considerable amount of investment.

C. Impact of Channel Spacing Within Superchannels

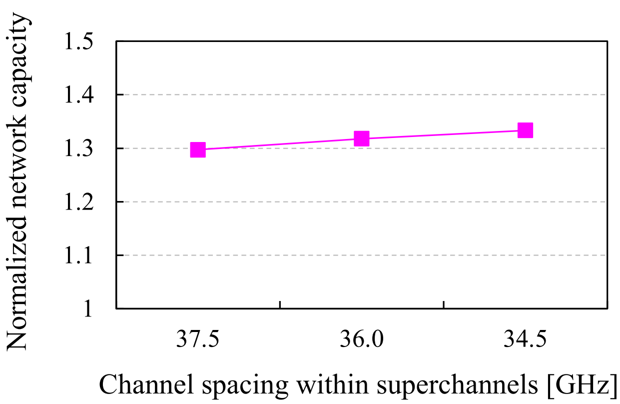
In order to further analyze the benefits of our solution, we evaluate the impact of channel spacing within superchannels on network performance. In this evaluation, three patterns of channel spacing (37.5, 36.0, and 34.5 GHz) are tested, and the impact of differences in topologies is also discussed. The number of accommodated requests before the first blocking occurs is measured for each pattern, just as Sect. IV. B.

Fig. 6 shows the obtained results, where the normalized network capacity is defined as the ratio of the accommodated requests achieved with our solution to that with conventional solution. Note that such a normalized value makes discussion about performance gain achieved by our solution easier. The results clarify that denser channel spacing can increase the available network capacity in both topologies. Furthermore, the impact of denser spacing is larger in the JPN12 topology. This is mainly because the JPN12 topology is a ladder-like structure that tends to cause traffic concentration and link congestion. It is quite natural that increasing channel density on congested links can effectively improve the total network performance. In addition, the performance gain achieved with our solution can reach 46% under the practical scenario, as shown in Fig. 6 (b). It should be emphasized that such capacity gains can be realized without the need for upgrading fiber infrastructure.

D. Impact on Hardware Volume

Moreover, to discuss the impact of the SChA-based in-network superchanneling on required hardware volume, the number of WCs used for channel (re)arrangement is measured for each scenario. Note that such a number is measured when the first blocking occurs. Naturally, WCs are the additionally required components compared to traditional ROADM-based optical networks, as depicted in Fig. 2. Also note that the required hardware volume is an important metric for network operators as less hardware volume generally leads to a space- and cost-effective solution.

The ratio of the number of activated WCs to that of deployed transponders (TRs) for each scenario is shown in Fig. 7. Note that this ratio is equal to 1 when the number of WCs and TRs



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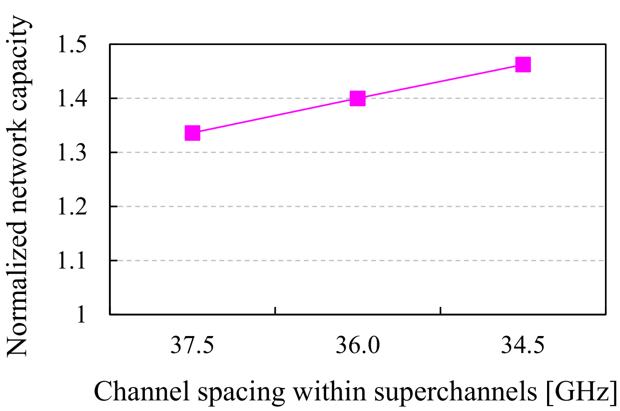

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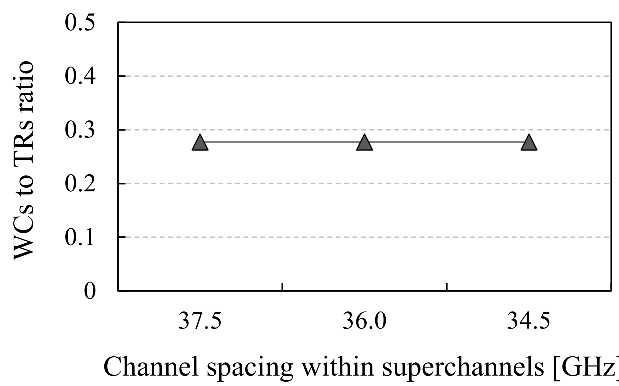
Fig. 6. Impact of channel spacing within superchannels on the performance of the proposed SChA-based solution.



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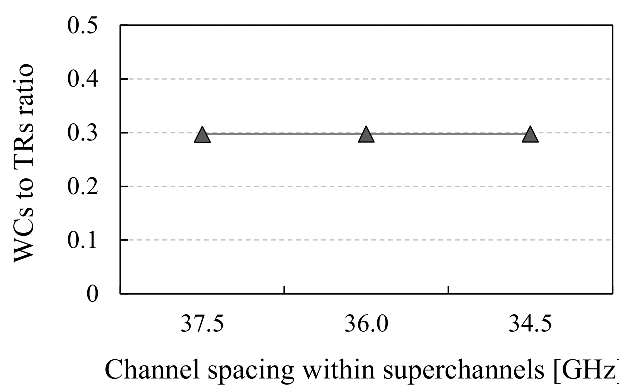

(b) JPN12

Fig. 7. Ratio of the number of WCs to that of TRs deployed throughout the network.

used is the same, where all the paths utilize in-network superchannel routing. On the other hand, the low WCs-to-TRs ratio means that additional hardware volume impact is reduced. The obtained results in Fig. 7 verify that the number of WCs is less than 30% of all TRs used for each scenario, regardless of the channel spacing within superchannels. This clarifies that our solution can remarkably improve network capacity (as shown in Fig. 6) without significant increase in hardware volume in terms of optical components.

Specifically, our solution can be activated by installing a limited number of WCs in certain nodes (not all nodes). Also, it is worth noting that our solution does not require any special assumptions on TRs at both end nodes, which is the key feature of "in-network" superchannel routing. This allows any embedded TRs or coherent pluggable optics to be flexibly utilized as long as transmission performance, i.e., transmission reach is well considered and ensured. The proposed solution introduces a new degree of flexibility in optical networking.

V. Conclusions

This paper re-explored the potential of superchannel concept in the era when traditional C-band capacity is saturating. In particular, we proposed and investigated a node subsystem towards flexible superchannel-enabled networking. Unlike conventional solutions, our proposal enables paths to utilize superchannel routing even between intermediate nodes on the route, and spectrum resources are adaptively utilized while minimizing spectrum wastage. Numerical results demonstrated that our solution contributes to further network capacity expansion using the existing fiber infrastructure. Moreover, through parameter sensitivity analyses, we clarified that capacity gain achieved with our solution can reach 46% by installing a limited number of wavelength converters. This opens the opportunity for advanced optical networking using superchannels and wavelength conversion.

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