

Virtual Fiber Networking and Impact of Optical Path Grooming on Creating Efficient Layer One Services

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SUMMARY This paper presents a novel “virtual fiber” network service that exploits wavebands. This service provides virtual direct tunnels that directly convey wavelength paths to connect customer facilities. To improve the resource utilization efficiency of the service, a network design algorithm is developed that can allow intermediate path grooming at limited nodes and can determine the best node location. Numerical experiments demonstrate the effectiveness of the proposed service architecture.

key words: waveband, optical path grooming, virtual fiber networking, virtual private network, layer one service

1. Introduction

Layer 1 virtual private network (VPN) services or broadband on demand services such as JiT (Just in Time) [1] and Optical Mesh Service [2] have been deployed in North America and other countries. They currently utilize TDM SONET/SDH digital paths. At the end of 2008, private networks were estimated to account for 20 percent of international bandwidth usage [3]. In the future, the service bandwidth will naturally increase to 10 Gbps or more, which necessitates lambda leased line or dynamic lambda services. In addition, leased fiber (dark fiber) service is presently utilized to create private networks for enterprise networking, data center networking, and for education and research use [4]. A recent analysis by one of the largest Tier-1 ISPs in North America shows that line rate private line service traffic accounts for 15%, while low and high rate private line service traffic accounts for almost 20% of the core segment network traffic [5]. The available fiber bandwidth is increasing thanks to recent advances in transmission technologies which include digital coherent technologies. The available bandwidth per single fiber recently reached 101.7 Tbps [6]. The fiber bandwidth is thus continuing to increase and most users will not need to lease fibers to create private networks. The bandwidth gap between lambda leased line service and leased fiber service will be efficiently bridged by the introduction of an intermediate bandwidth granularity service based on wavebands, the “virtual fiber” service (in this paper, waveband and virtual fiber are used interchangeably). The introduction of virtual fiber will help carriers to minimize the consumption of precious fiber resources, and users

will be serviced cost-effectively.

This paper proposes the Layer 1 virtual fiber network service that utilizes wavebands. For the proposed network, we also evaluate the effect of introducing wavelength path grooming, switching wavelength paths between waveband paths, at just a few limited nodes, the “grooming nodes”. This means that carriers do not only lease virtual fibers, but also provide wavelength path switching at a few nodes as necessary. The introduction of grooming is expected to greatly enhance the performance or resource utilization of virtual fiber networks. We propose an algorithm that can determine the best grooming node positions and the routes of virtual fibers for each virtual fiber private network so as to maximize the performance of the private networks while minimizing their cost. In this paper, the performance of private virtual fiber networks is measured by the blocking probability of wavelength path demands between customer sites and dedicated network resource requirements. Numerical results demonstrate the impact of introducing grooming nodes on the blocking probability and effectiveness of the proposed algorithm. The important point to be noted is that the performance improvement is attained with marginal switch cost increase. In other words the performance improvement is attained by grooming just a very small percentage of wavelength paths.

2. Preliminary

The present explosive traffic increase is driving the introduction of single layer optical path networks that utilize wavelength path routing with optical cross-connects (OXC) or multi-degree ROADMs; a large number of ROADM ring networks have been deployed in North America and Japan. In order to enhance optical routing capability, the hierarchical optical path network that introduces higher order optical paths, wavebands, i.e. bundles of multiple wavelength paths, has been investigated [7]–[12]. The effectiveness of the network has been verified through the development of efficient network design algorithms [13]–[21] and advanced hardware devices [22]–[24]. In hierarchical optical path networks, each node hosts a hierarchical optical cross-connect (HOXC) that consists of a wavelength cross-connect (WXC) for routing wavelength paths and a waveband cross-connect (BXC) for routing waveband paths (See Fig. 1). There are two major switch architecture alternatives for HOXC construction; One is based on WSS/WBSS (Wavelength Selec-

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tive Switch/Waveband Selective Switch) and the other on matrix switch type. The hardware scale of the BXC portion can be quite small if matrix type or 3-D MEMS type optical switches are utilized [7].

The ideal situation for applying wavebands is that all wavelength path demands are accommodated within direct wavebands that connect source and destination nodes and all waveband paths are filled by wavelength paths. Figure 2 plots the relationships among the ratio of optical cross-connect port number R , the waveband capacity W , and the average number of waveband hops H , for a hierarchical optical path network [20]. The optical cross-connect port number ratio, R , is the ratio of necessary number of switch ports for a hierarchical optical path network to that for a conventional single layer optical path network. The area where R is smaller than 1 is the effective area for introducing hierarchical optical paths. The figure confirms that hierarchical optical path networks can be cost-effective over a wide range of parameter values of H and W . In matrix type switches, the hardware scale (evaluated by the necessary number of component 2×2 switches) is basically proportional to the square of the port number, and hence the hardware scale can be reduced to 1/100 by the introduction of hierarchical OXCs. Regarding the WSS/WBSS based HOXC system, a single chip WBSS has been successfully developed using PLC technologies [22]. The device has no moving mechanical parts, requires no adjustment, and is very compact,

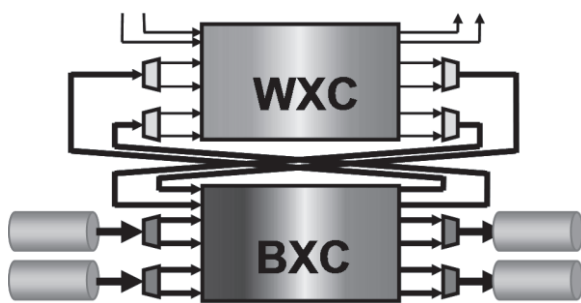


Fig. 1 Hierarchical optical cross-connect.

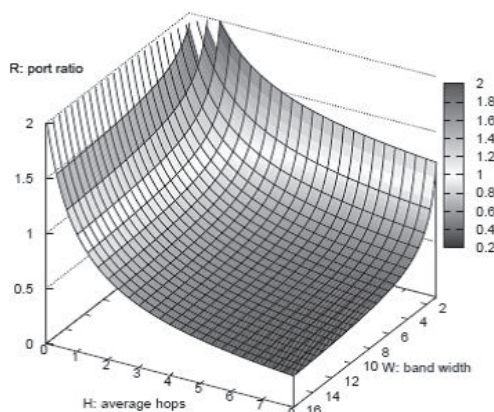


Fig. 2 Ratio of necessary number of switch ports for a hierarchical optical path network to that for a conventional single layer network.

which will lead to high reliability and low cost. Using the WBSS, an ultra-compact ($12.5 \times 21 \times 5 \text{ cm}^3$) one box 5×5 BXC module has been developed [23]. Each input fiber carries forty 100 GHz spaced wavelengths in five wavebands; each waveband holds eight wavelengths. The total throughput is 2 Tbit/s ($10 \text{ Gbps} \times 40 \lambda \times 5 \text{ fibers}$). Combining two of the modules with their channel grid frequencies offset by 50 GHz, and using 50–100 GHz interleavers upgrades the system throughput to 4 Tbit/s. The virtual fiber service can exploit these kinds of BXC technologies to create compact and cost-effective nodes. The HOXC node usually employs WXC switches in addition to BXC, and the effect of utilizing the WXC function is also investigated below.

3. Virtual Fiber Private Networking in Hierarchical Optical Path Networks

In the evaluations, wavelength paths are assumed to be always accommodated in waveband paths and the routing at intermediate nodes is done at the waveband granularity level (Fig. 3). In addition to a leased-fiber based VPN, when demands are smaller than the available fiber bandwidth, the use of waveband paths, an intermediate granularity, reduces the unused bandwidth in the VPN allowing a cost-effective VPN to be constructed (Fig. 4). In the example shown in Fig. 5, the proposed VPN connects four nodes with four waveband paths, where each node provides access from customer site. Only node G, an intermediate node, in Fig. 5 provides grooming capability; it can terminate waveband paths to allow wavelength path switching to a different waveband path. By introducing the grooming nodes, the utilization ratio of the waveband VPN is expected to be substantially improved. Robustness against traffic variation is another important benefit provided by the VPN, and this also can be enhanced since the spare capacity in each waveband can be dynamically assigned when necessary in response to the traffic demand changes among the VPN customer sites.

In the following virtual fiber private network analysis,

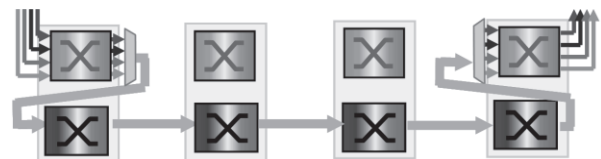


Fig. 3 Port occupation by wavebands.

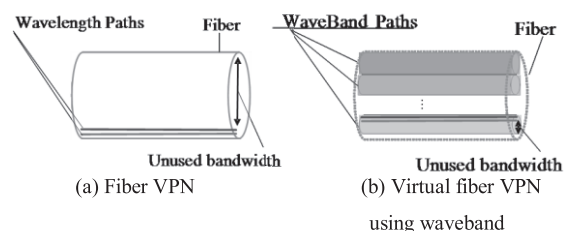


Fig. 4 Efficient bandwidth utilization by introduction of waveband virtual fiber VPN service.

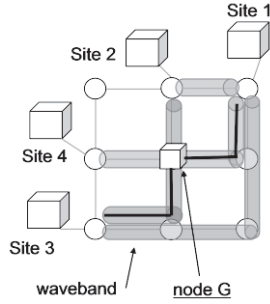


Fig. 5 Waveband based VPN.

we assume that we must construct a VPN that interconnects specified nodes with sufficient capacity to accommodate a number of wavelength path demands between all node pairs. In addition to this, we evaluate the effectiveness of introducing the grooming node. Grooming should be kept minimum, and hence the number of grooming nodes is kept very small, say, one or two. In this situation, where to site the grooming node is very important in maximizing the expected grooming effect. To attain this, the proposed network design and the evaluation process consist of two stages. The first stage constructs the initial VPN to meet the expected traffic volume, which includes routing of waveband paths and optimization of grooming node placement. The second stage evaluates dynamic wavelength path operation. The initial stage is constructed as follows.

(Routing of waveband paths and optimization of grooming node placement)

Step 0. Initial Setup

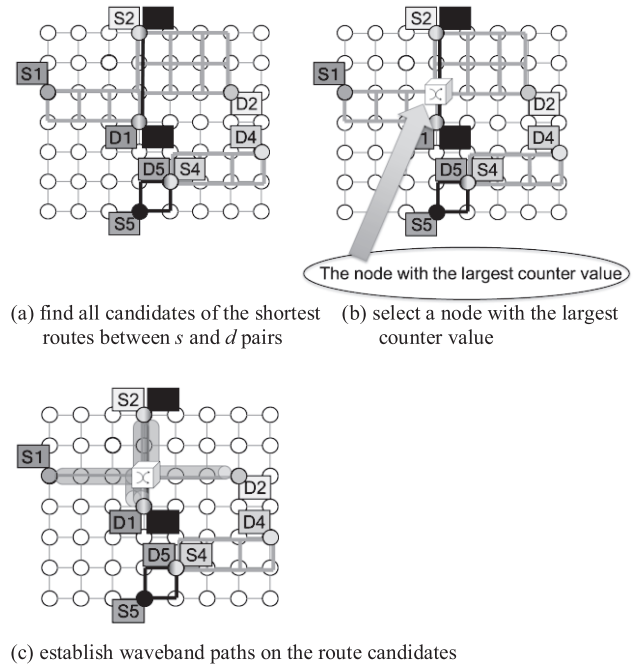
Multiply the expected number of wavelength paths between each node pair by factor α (≥ 1), an accommodation margin to achieve the desired blocking probability, round the result up to the nearest integer. (The value of α can be determined iteratively. In order to settle on an accurate value of α , we iteratively apply the proposed method and evaluate blocking probability on the network. That is, if the estimated blocking probability on the network is not close enough to the desirable level, we increase/decrease the value of α and evaluate the blocking probability again. By repeating this process, we can find an appropriate α value.) Calculate the necessary and sufficient waveband paths between the node pairs to accommodate the scaled wavelength path demands.

Step 1. Check on Termination Condition

If the number of selected grooming nodes is less than a given threshold, go to Step 2. Otherwise, for unaccommodated wavelength path demands, establish waveband paths between source and destination nodes using the shortest routes and accommodate the demands in these paths.

Step 2. Selection of Grooming Node Placement

Set an integer-valued counter in each node to count the spare waveband capacity and let all the counters



(a) find all candidates of the shortest routes between s and d pairs (b) select a node with the largest counter value

(c) establish waveband paths on the route candidates

Fig. 6 Routing of waveband paths and optimization of grooming node placement.

be zeroed. For all waveband path demands that have yet to be accommodated in fibers, find all candidates of the shortest routes between source and destination nodes, see Fig. 6(a). For each demand, increment the counter by the number of wavelength paths that can be accommodated within the spare capacity of the waveband path for all intermediate nodes of the routes. Finally, the counter value gives the maximum total spare capacity that can be utilized to reach the node (to accommodate the path demands). Select a node with the largest counter value from among all nodes, except for already selected grooming nodes, and let the node be a new grooming node, see Fig. 6(b). If multiple nodes share the same, largest, counter value, one of them is selected randomly.

Step 3. Establishment of Waveband Paths

For waveband path demands one of whose route candidates passes through the newly selected grooming node in Step 2, establish waveband paths on the route candidates, see Fig. 6(c). Accommodate the demands in the established waveband paths. Go back to Step 1.

After completing the above VPN construction stage, we move to the second stage. For each wavelength path establishment request, we try to allocate a wavelength in a direct waveband path connecting source and destination nodes. If a spare wavelength channel exists in the waveband, allocate it and establish the wavelength path. Otherwise, we try to find a pair of concatenated waveband paths that have spare capacity each of which connects the source to grooming node and the grooming node to the destination. If there is such a pair of waveband paths, we establish a wavelength

path in the same manner. Otherwise, the request is blocked.

4. Numerical Experiments

4.1 Reduction of Switch Port Utilization

In order to clarify the impact of using wavebands, we analyzed the number of utilized switch ports for single layer and hierarchical optical leased line networks; intermediate grooming was not applied. The numbers of required switch ports normalized by the numbers required for a single layer optical path cross-connect for a 9×9 regular mesh network (Fig. 7) and the COST266 pan-European network (Fig. 8) are shown in Figs. 9(a) and (b), respectively. Number of customer sites for 9×9 and COST266 networks were set at nine and five, respectively, and their locations were randomly selected in each simulation trial. Expected customer wavelength path demands between all node pairs were uniformly and randomly distributed. The target blocking probability was set at 0.01. The average utilization ratios of wavebands are also shown in Figs. 9(a) and (b). In the evaluations, each waveband can accommodate up to 8 wavelengths, and each fiber can accommodate 8 wavebands (in total, 64 lambdas). The utilized port count is reduced over a wide range of traffic demand while waveband paths have sufficient spare capacity to accommodate fluctuations in the traffic demands. The impact of using wavebands is larger for the 9×9 regular mesh network than for the COST266 pan-European network. This is because the former has larger average hop count than the latter and so the port count reduction attained by waveband routing is more significant.

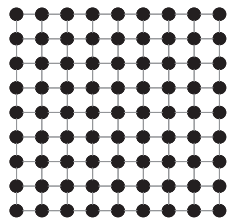


Fig. 7 9×9 regular mesh network.

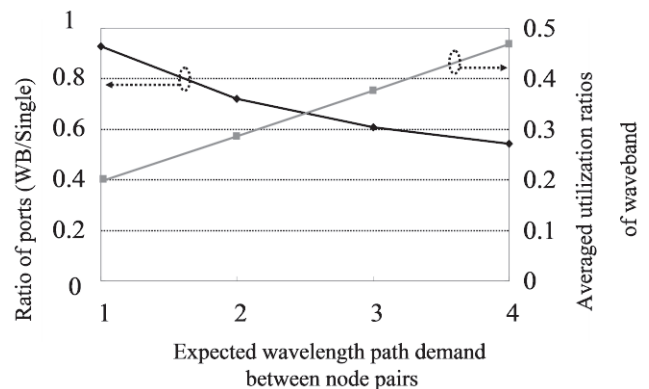


Fig. 8 COST266 network.

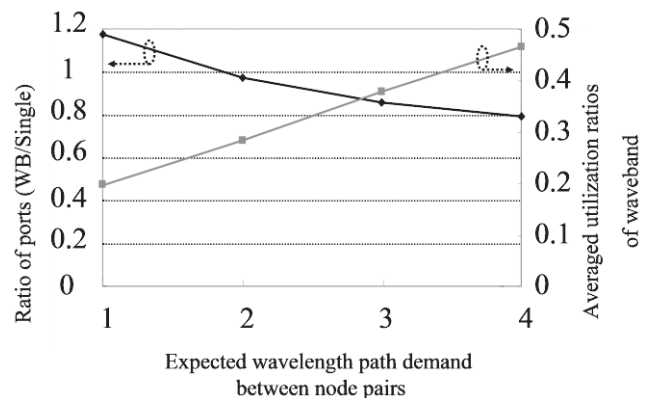
4.2 Impact of Intermediate Grooming

We evaluate the performance of the proposed virtual fiber VPN in terms of the blocking probability against dynamic wavelength connection demands for the two topologies shown in Sect. 4.1. Expected wavelength path connection demands are determined in the same manner as in Sect. 4.1. Wavelength path connection demands follow a Poisson distribution. The connection holding time follows a negative exponential distribution and the average holding time is determined so that the average number of wavelength paths between each node pair is the expected demand. The number of customer sites matches that in Sect. 4.1.

First of all, we evaluated the necessary traffic scale factor, α , which is introduced to achieve the desired blocking probability (See STEP0 of the proposed algorithm). In this numerical experiment, in order to evaluate the impact of introducing grooming nodes, we first calculate α that achieves a blocking ratio of 0.01 on a waveband VPN network without any grooming node. The value of α used was 1 for the average demand of 1, and 1.7 for average demands of 2, 3, and 4. We then fixed the necessary VPN resources and evaluated blocking ratios on the VPN that used one or more grooming nodes. Even though a wavelength path may go



(a) 9×9 regular mesh network



(b) COST 266 pan-European network

Fig. 9 WB utilization ratio and necessary optical switch port ratio.

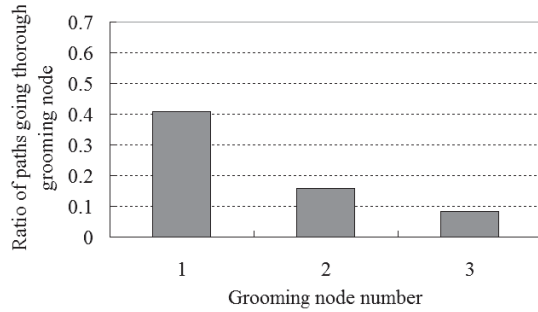
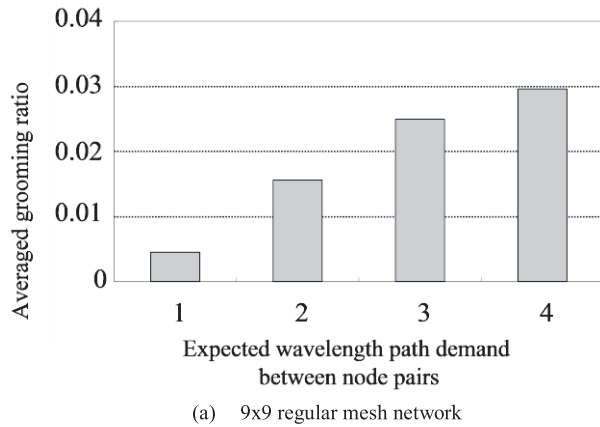
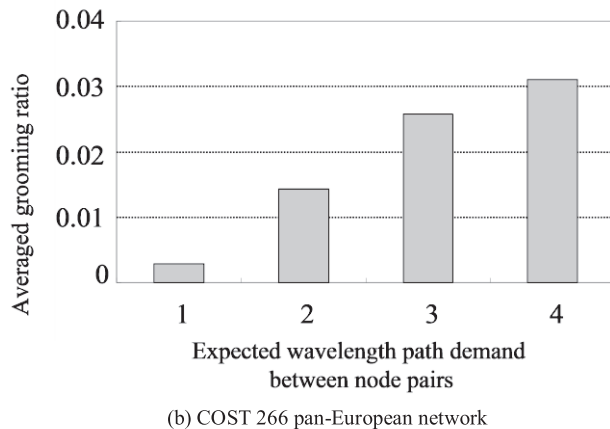


Fig. 10 Ratio of waveband paths going through grooming nodes.



(a) 9x9 regular mesh network

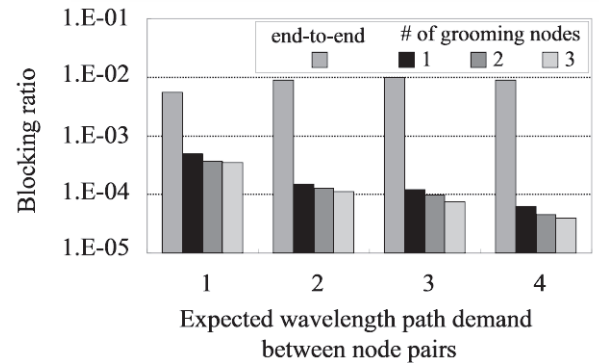


(b) COST 266 pan-European network

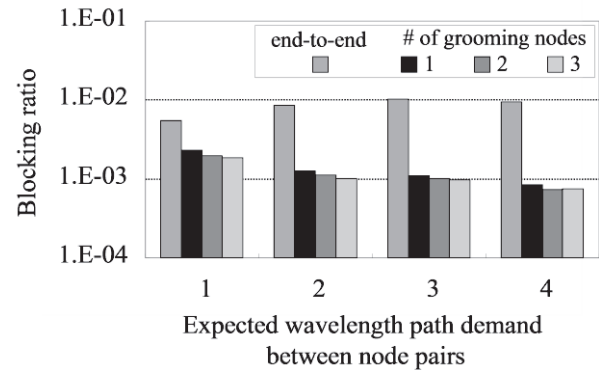
Fig. 11 Averaged grooming ratio.

through multiple grooming capable nodes, we allow only onetime grooming operation for each waveband.

Figure 10 illustrate how many waveband paths can go through grooming nodes with optimum locations. We assumed in these emulations that the network topology is a 9×9 mesh network and the average number of paths between each node pair was 4. The number of grooming nodes is incremented from one to three. Figure 10 indicates that when there is only one grooming node in the private network, route candidates of almost 40% of the waveband paths go through the grooming node. If the second grooming node is introduced, an additional 15% of the waveband paths go



(a) 9x9 regular mesh network



(b) COST 266 pan-European network

Fig. 12 Averaged blocking ratio.

through the second grooming node. This means that the introduction of a single grooming node provides the most significant impact.

As wavelength path demand increases, more waveband paths will be filled. This triggers the detouring of wavelength paths to other waveband paths through the grooming function. This can be verified by the results shown in Figs. 11(a) and (b), which show the average grooming ratios, the ratios of wavelength paths that experienced intermediate grooming to the total number of wavelength paths.

The blocking ratios are shown in Figs. 12(a) and (b). Introducing one grooming node substantially reduces the blocking probability while additional grooming nodes provide only minor reductions in the blocking probability. This is because, our proposed algorithm, described in Sect. 3, first selects the node that has the maximum counter value, i.e. the sum of the unused wavelengths in waveband paths that can go through the node. The second selected node has a counter value smaller than that of the first selected node. Moreover, for the first selection, we consider all waveband paths whose route candidates go through the node whereas waveband paths that go through the first selected node are not considered in the second selection. As a result, the first selected node aggregates many more waveband paths that have unused wavelengths than the second node, and hence the improvement attained by increasing the number of grooming nodes decreases rapidly. Figure 10 indicates that the first

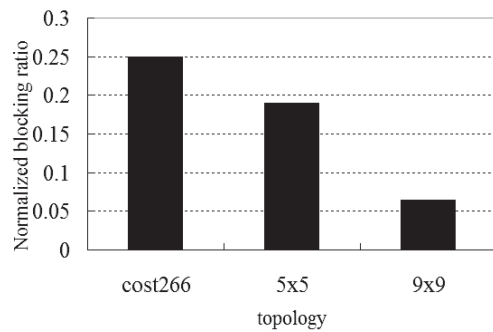


Fig. 13 Blocking ratio reduction by using grooming.

grooming node aggregates 40% of all waveband paths, the second takes 15%, and the third takes 9%.

Figure 13 shows how the grooming function is effective in reducing blocking ratios for different topologies. The vertical axis plots the blocking ratio normalized by that when end-to-end wavebands are utilized, i.e., without grooming; the blocking ratio was set to 0.01 for each topology. The traffic intensity was set at 1.4. The lowest ratio (the largest improvement) is achieved for the 9×9 regular mesh network. This is due to the fact that the regular structure has many shortest route candidates for connecting each node pair and, therefore, many node pairs have route candidates set in the waveband VPN network that has one grooming node. A 5×5 regular mesh network also has a regular structure, however, the impact is limited since there are fewer route candidates for each node pair than the 9×9 regular mesh network. The COST 266 network exhibits the smallest impact because of its asymmetrical topology.

5. Conclusion

We proposed a virtual fiber VPN service that utilizes waveband paths and waveband cross-connects. The impact of wavelength grooming was confirmed by developing a network design algorithm that optimizes grooming node location. It is clarified that the introduction of one grooming node can reduce the blocking probability by more than two orders of magnitude, even though the grooming ratio is very small, under 3 percent. This means that the control processing burden in PCE (Path Computation Element) can be light and the switch cost increase is limited. Of course the necessity of introducing grooming capability depends on the requirement on the VPN, and will not be always necessary. Simple virtual fiber (waveband) leased line networks will provide attractive services since carriers can minimize the consumption of precious fiber resources and users can access cost-effective services.

Acknowledgments

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He has authored/co-authored more than 300 research publications in international journals and conferences. He holds 35 granted patents and more than 100 pending patents. He received his B.S., M.S., and Ph.D. degrees in electronics engineering from the University of Tokyo, Tokyo, Japan, in 1976, 1978, and 1986, respectively. He received the Young Engineer Award in 1984, the Excellent Paper Award in 1991, and the Achievement Award in 2000 from the Institute of Electronics, Information and Communication Engineers (IEICE) of JAPAN, and the best paper awards in 2007 and 2008 from the IEICE Communications Society. He was also the recipient of the distinguished achievement Award of the Ministry of Education, Science and Culture in 2002. His contributions to ATM (Asynchronous Transfer Mode) and optical network technology development extend to co-editing three IEEE JSAC special issues and the IEEE JLT special issue once, organizing several Workshops and Conference technical sessions, serving on numerous committees of international conferences including OFC and ECOC, authoring a book, *Advances in Transport Network Technologies* (Artech House, 1996), and co-authoring thirteen other books. He is a Fellow of the IEEE.