

## PAPER

# Optical Fast Circuit Switching Networks Employing Dynamic Waveband Tunnel

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**SUMMARY** We propose a novel dynamic hierarchical optical path network architecture that achieves efficient optical fast circuit switching. In order to complete wavelength path setup/teardown efficiently, the proposed network adaptively manages waveband paths and bundles of optical paths, which provide virtual mesh connectivity between node pairs for wavelength paths. Numerical experiments show that operational and facility costs are significantly reduced by employing the adaptive virtual waveband connections.

**key words:** hierarchical optical path network, optical circuit switching, routing and wavelength assignment, waveband, dynamic control

## 1. Introduction

Due to the rapid penetration of broadband access including Asymmetric Digital Subscriber Line (ADSL) and Fiber-to-the-home (FTTH), the amount of Internet traffic has increased at an explosive rate all over the world. This large increase in traffic demand has driven the introduction of reconfigurable optical add/drop multiplexer (ROADM)-based photonic networks, in which optical signals are routed without opto-electrical (O/E) and electro-optical (E/O) conversion [1], [2]. At this stage, the optical/wavelength paths are operated on a provisioning basis or almost statically and transport aggregated electric paths such as Internet Protocol-Label Switched Paths (IP-LSPs), Virtual Containers (VCs), and Optical-channel Data Units (ODUs), which carry existing services.

The current network architecture has evolved to match data-centric services such as web browsing, E-mail, file transfer, and limited-bandwidth video streaming. Recent advances in video technologies will cause the traffic volume to escalate steeply in the near future. The introduction of bandwidth intensive video applications such as 4-k Cinema (2k x 4k pixels, 6 Gbps per channel) has already started and Ultra-High Definition TV (4k x 8k pixels, 72 Gbps per channel) will be available within ten years [3]. Because of the huge required bandwidths, it is expected that video will be the dominant application in terms of traffic volume in the future. Furthermore, new network services will emerge such as layer one virtual private network (VPN) service, lambda leased line service, and e-science, all of which require enormous bandwidth [4]–[6]. Future networks must

be able to handle efficiently such new services the traffic characteristics for which can be very different from current traffic, i.e., they occupy a large bandwidth for a certain duration. Layer 3 IP routers are not efficient in managing these bandwidth intensive and stream like services that can occupy the full capacity of a wavelength path [7]. To actualize future networks that can provide abundant bandwidth with minimum energy consumption, optical paths/circuits must be operated dynamically. For example, the current nationwide TV program distribution network in Japan provides High Definition TV quality programs, that is, the channel bit rate is approximately 1.5 Gbps, and the distribution pattern changes every hour or so, which requires more than 40,000 transfer/distribution pattern switchovers in the network in a year. In the future, one Ultra-High Definition TV program channel, which will reach 72 Gbps, will occupy the wavelength capacity, and hence the application will need optical fast circuit switching. Regarding optical circuit switching, clarification of the terminology is given below. Connection establishment/tear-down is triggered by either external control or is traffic driven. We call the former optical circuit switching and the latter optical flow switching. The connection establishment/tear-down speed for optical circuit switching or optical flow switching can be enhanced by a fast signaling mechanism that will be attained by employing a waveband tunnel that will be discussed in this paper. In the following, triggers for connection establishment/release procedures are not discussed, and optical circuit and flow switching are not distinguished because these are issues independent from the architectural issue of tunneling.

In this paper, we introduce an efficient network architecture that is suitable for transporting less-bursty (video) but quality-demanding high bit rate real or almost real-time services. Optical fast circuit switching (OFCS) technology will play a key role in accommodating such services [7], [8]. OFCS dynamically establishes end-to-end wavelength paths (path and circuit are used interchangeably in this paper) connecting source and destination node pairs to accommodate large volumes of traffic. The network needs to control dynamically a large number of optical paths. Hence a sophisticated architecture is necessary to reduce the operation, administration, and maintenance (OA&M) costs.

As a cost effective and bandwidth-abundant network solution, hierarchical optical path networks that utilize waveband paths, i.e., a bundle of wavelength paths, was proposed and has attracted attention due to its large bandwidth switching capability [9], [10]. The introduction of wave-

Manuscript received January 23, 2012.

Manuscript revised May 27, 2012.

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DOI: 10.1587/transcom.E95.B.3139

bands can reduce the optical switch size at cross-connects, which substantially mitigates the problem in developing large optical path cross-connect systems. It was also shown that the hierarchical path structure significantly reduces the total network cost [11]–[13], which was proven for static optical path network design, i.e., establishment of optical paths to accommodate a given static traffic demand. The wavebands can also provide an efficient protection mechanism for failure recovery [12], and can effectively limit the full Colorless/Directionless/Contentionless (CDC) flexibility which is useful to minimize CDC related hardware [14], [15].

However, how to make the best use of the hierarchical optical path structure for developing efficient dynamic path operations has not yet been investigated. Some conventional works [16]–[18] on dynamic control of hierarchical optical path networks exist, however, they considered the improvement of path routing algorithms that is only verified on hierarchical optical path networks by using a conventional measurement, blocking probability. In other words, we must verify how the path hierarchy not only reduces the facility cost but also simplifies the path establishment and release procedure. In this paper, we utilize the average number of nodes involved in each procedure as a measure of complexity in path establishment and release procedures. We call this measure signaling cost whereas facility cost is defined as the sum of costs of all key components. Our preliminary study in [19] considered hierarchical physical networks and introduced coarse granular switching only to a part of the physical networks. The lower layer network consists of many domains, each of which is an independent network that employs no optical path hierarchy. The upper layer network connects these domains and establishes an optical path hierarchy. The upper layer network connects source and destination transit switching nodes in the lower layer sub-networks with direct waveband paths. This model well reflects the present hierarchical structure of core/metro networks, and the results of numerical experiments proved its lower operation and facility costs compared to networks that do not use the hierarchical optical path structure. In the future, the number of optical paths to be operated in each sub-network will increase, and hence the introduction of wavebands should be more extensive all over the network. Thus the next task will be to evaluate how the introduction of a new network architecture that utilizes the optical path hierarchy will reduce not only facility cost but also path operation complexity.

In this paper, we propose a novel OFCS network architecture that utilizes wavebands throughout the network, and elucidate its impact on network cost and path operation cost. In the network, waveband paths are adaptively established/removed to provide virtual mesh connectivity between any node pair so as to carry efficiently wavelength paths to prevent fine granular wavelength switching at intermediate nodes. Dynamic intermediate grooming of wavelength paths into waveband paths is also proposed, which is required to improve the waveband/fiber utilization ratio in

hierarchical networks. The number of intermediate grooming for each wavelength path will be bounded to keep the efficiency in path operation. Numerical experiments demonstrate that the proposed hierarchical network architecture can reduce network resources as well as the number of path operations. It is shown that the reduction is enhanced as the network scale expands and the traffic volume increases.

A preliminary version of the work was presented at an international conference [20].

## 2. Comparison of Electrical and Optical Domain Technologies

In this section, brief explanations are given on the path architectures and services that are achieved using electrical and optical technologies. Comparisons between electrical and optical technologies are presented.

In terms of path bandwidth, Asynchronous Transfer Mode (ATM) Virtual Path or Packet LSPs can provide flexible bandwidth. On the other hand, the bandwidth of TDM paths such as VCs in SDH, ODUs in the Optical Transport Network (OTN), and optical paths is fixed. In order to enhance the flexibility, hierarchical structures have been defined for electrical paths as shown in Fig. 1. The lower order paths provide service access, while the higher order paths generally provide transmission access [8]. At present, in the optical domain, a wavelength path (channel) is defined and utilized as a single order entity. As the traffic demand and fiber transmission capacity increases, much larger bandwidth optical paths such as the waveband will be introduced, as was the case in electrical technologies. When optical layer services such as Optical Virtual Private Network (OVPN) services, lambda leased line services, optical circuit or optical flow switching services emerge, the hierarchical optical path arrangement will play a key role in the provisioning of the services as explained in the next section. From physical transmission point of view, to implement agile optical wavelength services, optical amplifiers that allow dynamic wavelength switching are necessary. Such amplifiers are already studied and developed, which are utilized

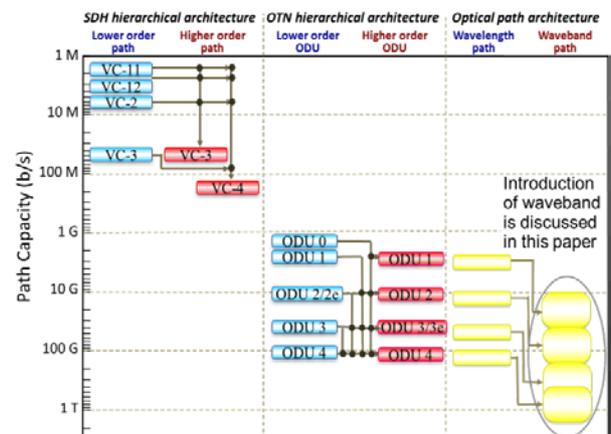


Fig. 1 SDH, OTN, and OP architectures and path capacities.

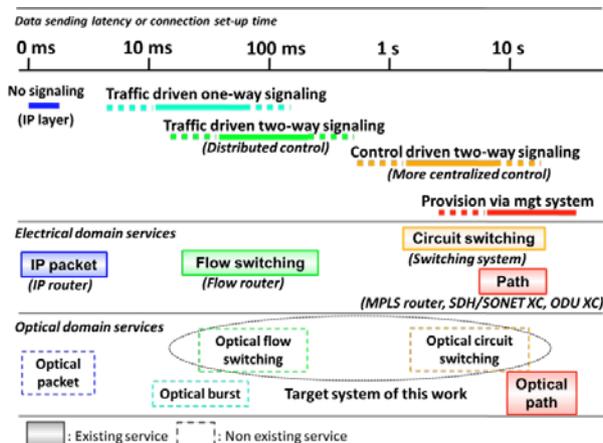


Fig. 2 Connection set-up time, and electrical and optical domain services.

in the optical packet transmission experiments and the performance is verified [21].

Figure 2 illustrates data sending latency or connection set-up time for present electrical services and optical services. In electrical domain services, IP datagram service does not utilize signaling and therefore, information is sent immediately. Control driven two-way signaling is utilized for Public Switched Telephone Network (PSTN), and traffic driven two-way signaling is utilized for IP flow switching. Electrical paths are controlled by management systems and therefore, path set-up time tends to be longer. At present, in the optical domain, only the optical paths are practically utilized, which are also controlled through management systems. The target systems discussed in this paper are optical fast circuit switching and optical flow switching, which are expected to be implemented not so far in the future as soon as the demands that are discussed in the introduction section emerge.

### 3. Hierarchical Optical Circuit Switching Network

Figure 3 depicts a hierarchical structure of optical paths and the node structure. The optical cross-connect consists of a waveband cross-connect (BXC) and a wavelength path cross-connect (WXC). Figure 4 shows a network model and illustrates the optical path establishment process (a) in a conventional single optical path layer network and (b) in a multilayer optical path network. As in Fig. 3, each node in the hierarchical network consists of a BXC and a WXC whereas each node in the single layer optical path network incorporates only a WXC [22], [23]. In the single layer network, optical path establishment/tear-down requires node (optical cross-connect)-by-node optical switch setting. Several dynamic wavelength path operation algorithms have been studied so far (for example, [24]), where wavelength path operations are performed based on the original physical fiber topology. On the other hand, in hierarchical optical path networks, wavelength path establishment can be performed by utilizing one direct waveband path or mul-

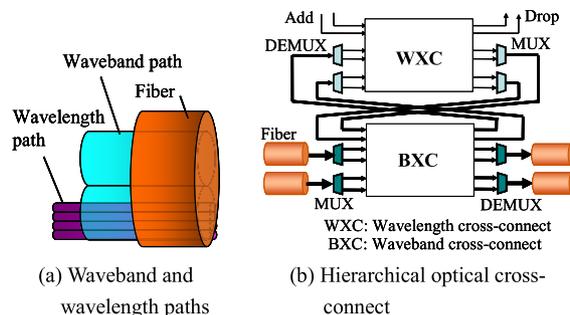


Fig. 3 Optical path hierarchy and cross-connect configuration.

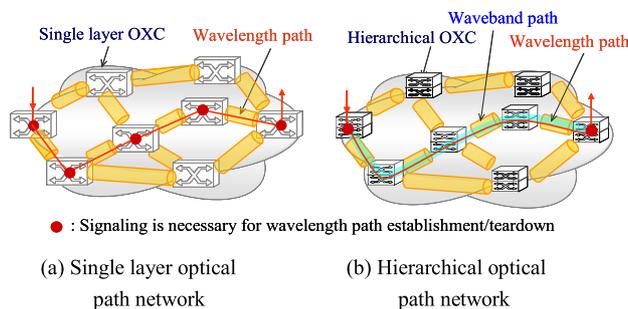


Fig. 4 Comparison of single layer optical path network and hierarchical optical path network.

iple concatenated waveband paths to connect the source and destination of the wavelength path. This means that in the connection establishment/release phase, the number of nodes involved is greatly reduced and the connection set-up/release delay is minimized. The waveband connections between nodes provide virtual tunnels that connect the distant nodes directly and hide the original physical topology. Furthermore, wavebands are immediately torn down if they do not have any wavelength paths to accommodate. This scheme however requires bandwidth reservation even when the optical paths/circuits to be accommodated within the waveband do not exist. This results in reduced resource utilization. The relationship between the optical wavelength path cross-connect and the waveband cross-connect corresponds to that of the electrical switching system and the cross-connect system in PSTN. With regard to connection establishment and signaling, centralized or distributed control schemes can be applied as demanded by service requirements. This is outside the scope of this paper.

The waveband bandwidth that we considered here ranges from 4 to 16, as explained in Sect. 5. Please note that in present PSTN, we use VC-11 (Virtual Container 11, used in North America and Japan) that accommodates 12 telephone channels. The higher order paths of VC-3 and VC-4 are utilized to connect telephone switching nodes. These units have been utilized to create cost-effective worldwide telephone networks. In our proposed networks, waveband corresponds to the VC-11, and optical fibers that connect node systems correspond to STM-1, for example.

#### 4. Dynamic Hierarchical Path Operation

We assume that wavelength paths are established and released dynamically in response to connection requests. In static network design, all wavelength path setup demands are given in advance and we can pursue optimal grooming into waveband paths, which is an important point in the significant facility cost reductions attained by hierarchical optical paths. However, for the problem considered here, the dynamic path setup/tear down operations cause diversions from the optimal path grooming condition. Since the information on future connection is not available, we propose two heuristics based on the following path operation strategies that are only based on current connection information. First, if there already exists a waveband path with spare capacity that directly connects the source and destination nodes of a given connection request, the wavelength path is accommodated within the waveband path. In this case, no cross-connect switch setup operation is necessary at the intermediate nodes. Otherwise, we conduct the following operations depending on the situation.

##### 1) Establish a new waveband path

As shown in Fig. 5(a), in order to accommodate a new wavelength path request, a direct waveband path routed on one of the shortest routes connecting the source and destination nodes of the wavelength path is newly established considering waveband continuity. In this new waveband establishment process, optical switch operations for the connection setup are needed at every node on the route of a waveband path, which is equivalent to that in a single layer network.

##### 2) Routing considering waveband grooming

Figure 5(b) shows wavelength path routing using a concatenated series of waveband paths. The goal is to establish a wavelength path between the source and destination nodes while ensuring wavelength continuity. In order to select a wavelength index and waveband paths to accommodate the wavelength path, we adopt an all-search method. In

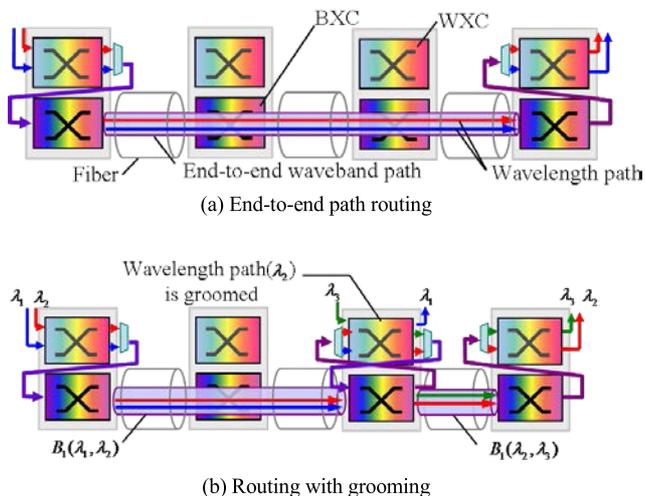
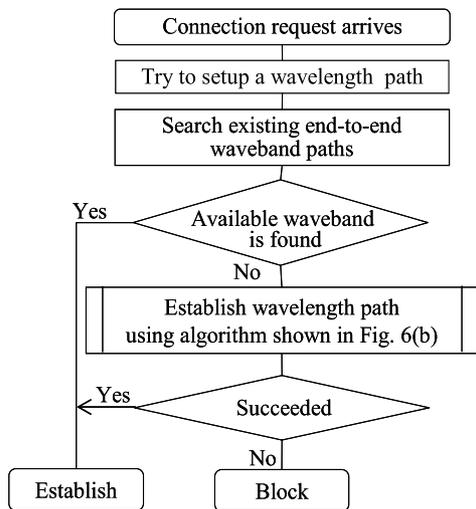


Fig. 5 Accommodation of wavelength path.

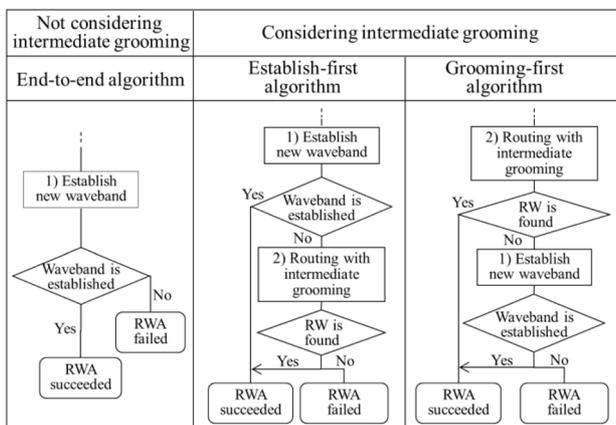
the scheme, first we define a multi-layered virtual topology where each layer corresponds to an individual wavelength and the links of the layer represent virtual connectivity that is created using existing waveband paths and the connectivity represents a vacant wavelength of the existing waveband paths. The link weight must represent the cost of the related waveband path. Considering the degree of the approximation that is valid for non-regular networks, where the longest and shortest link lengths can be very different, we define here a link weight for each virtual link that is based on the physical length of the related waveband path. For grooming operations, we assign a uniform weight much larger than the link weight; for example, 1000 times of the link weight. On each wavelength layer of the multi-layered virtual topology, the optimal route in terms of the total path length and grooming cost, i.e. minimum weight route, is calculated using Dijkstra's algorithm for the path establishment request [25]. The found route is the shortest one among the set of all pairs of a route and a wavelength that minimizes the number of traversed waveband paths. Finally, we select the set comprising the route and waveband/wavelength index that attains the lowest cost among all possible candidates in the multi-layered virtual topology.

Wavelength path connections are released when they become unnecessary. If some waveband paths become empty after the wavelength paths are removed, they are also deleted to increase spare network resources. The virtual topology is updated whenever a waveband/wavelength path is established or released. The introduction of intermediate grooming has both an advantage and disadvantage. The advantage is that it can increase the network resource utilization or the traffic volume that can be accommodated in the network, especially when there are many low utilized end-to-end direct waveband paths. This results in a reduction in the number of required fibers and Network-Network Interface (NNI) ports for the BXC. However, increasing the number of intermediate grooming is performed not only causes a longer circuit set up delay but also increases the required WXC switch size, which can be an issue considering the present technical situation in which switch device technology has not yet satisfactorily matured to achieve large-scale cross-connects cost effectively. Furthermore, in dynamic control, wavelength paths that traverse multiple waveband paths can hinder re-optimization of waveband paths since these waveband paths are fixed, i.e., cannot be removed, at least until the wavelength paths are removed. Therefore, the maximum number of waveband paths that can be traversed by each wavelength path should be limited to a sufficiently small number.

A block diagram of the proposed algorithm is presented in Fig. 6(a). Upon a new wavelength path request, if there already exists a waveband path with spare capacity that directly connects the source and destination nodes of a given wavelength path request, the wavelength path connection is established. Otherwise, an attempt is made to establish the connection using or not using intermediate grooming, the process for which is detailed in Fig. 6(b). Here, we use the



(a) General procedure



RW: A pair of route and wavelength  
RWA: Routing and wavelength assignment

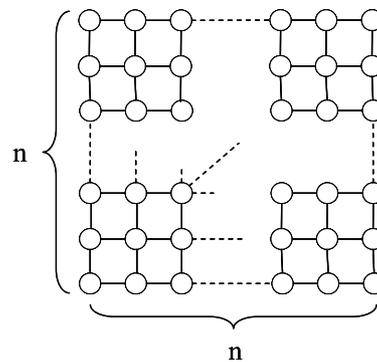
(b) Wavelength path set-up algorithms

Fig. 6 Connection set-up algorithms.

above procedures, 1) and 2), to accommodate a new path establishment request. We call the scheme that applies above procedure 1) first and then 2) as Establish-first (Fig. 6(b)). The converse is called Grooming-first. The latter is related to the conventional static design algorithms that pursue optimal grooming while the former aims at better adaptation to the current wavelength path demand distribution condition. Their performance is investigated in the next section. Regarding the computational complexity of the proposed algorithm, the minimum weight route calculation by Dijkstra’s algorithm is dominant. Therefore, the complexity of each path operation is  $O(|A| + |V| \log |V|)$  where  $|A|$  stands for the number of arcs and  $|V|$  that of nodes in the current multi-layered virtual topology [26].

### 5. Numerical Experiment

This section presents the quantitative evaluations conducted to verify the efficiency of the proposed hierarchical net-



(a)  $n \times n$  polygrid network ( $n = 5, 7, 9$ )



(b) COST 266 network

Fig. 7 Network topology.

works. We assumed  $5 \times 5$ ,  $7 \times 7$ , and  $9 \times 9$  polygrid networks and the COST 266 pan-European network as physical network topologies as depicted in Fig. 7. The distance between adjacent nodes in polygrid networks is fixed to 500 km. The distance in COST 266 is set at the real value. Optical amplifiers are inserted for every 60 km. We assumed that transparent transmission between any nodes is possible for all networks; i.e. no 3R regenerator is placed. Each fiber is set to accommodate 64 wavelengths paths, and they are uniformly divided into wavebands with the capacities of  $W = 4, 8, 16$ . The maximum number of possible grooming operations per wavelength path is set to two. Traffic demand (path connection requests) is uniformly distributed among node pairs and generated between each node pair following a Poisson distribution with an arrival rate of  $D$  ( $1 \leq D \leq 9$ ) [erl]. The connection holding time follows a negative exponential distribution the average for which is a unit time length. To evaluate the cost reduction yielded by the proposed architecture, we employ the conventional scheme, i.e., a single layer optical path network, with the same physical topology. The routing and wavelength/waveband assignment strategies in Sect. 4 are utilized for hierarchical optical path networks, whereas for single layer optical path networks, the vacant pair of route and wavelength that has minimum weight is always selected. The number of fibers on each link in hierarchical/single-layer networks was predetermined through static network design for a uniform traffic distribution. The number of fibers obtained by the static

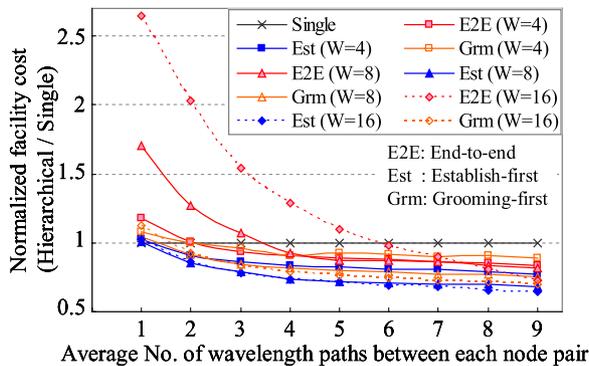


Fig. 8 Network facility cost evaluation in 7 × 7 grid network.

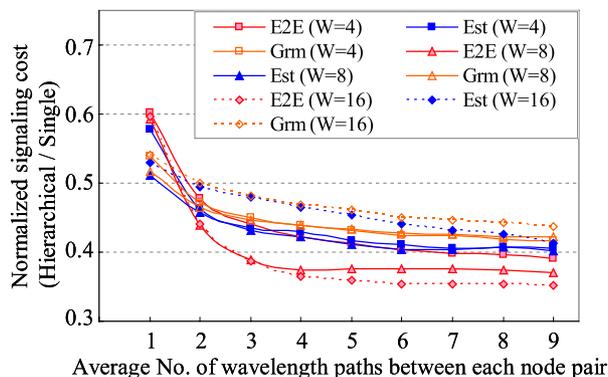


Fig. 9 Network signaling cost evaluation in 7 × 7 grid network.

network design is scaled for each traffic volume so that the blocking probability will be approximately 0.01, which is the target blocking probability, in the following dynamic operation stage. For example, in a 5 × 5 polygrid network that uses the proposed architecture, the average number of fibers at each link ranges from 4.15 to 9.625 depending on the arrival rate, D. The amount of traffic is proportional to the square of the number of nodes, the average number of fibers at each link increases as the network is enlarged. Differently from the static network designs mentioned above, dynamic operations on wavelength/waveband paths were conducted for the given dynamic path demands of arrival rate D.

### 5.1 Comparison of Routing Algorithms

Figure 8 shows the necessary facility costs of the hierarchical networks normalized by that of single layer networks, where almost the same blocking probability, 0.01, is achieved for both networks at each traffic volume. Here the network cost is evaluated by a sum of the node cost and the link cost ([11], see Appendix for detail). The node cost is derived from the total number of NNI and User-Network Interface (UNI) ports of the BXC and WXC, and the link cost is derived from the total number of fibers and amplifiers. The total facility cost is evaluated as the sum of these costs, i.e., a linear function of the number of facilities. Conventional studies that consider static single-layer/hierarchical optical path network design considered only the utilized facilities. For example, in a single layer network, if only two wavelength paths pass through a fiber, only the two wavelength-related ports are prepared at connected nodes and the cost is counted. On the other hand, for dynamic optical path networks we always prepare the maximum number of necessary ports that can attain the target blocking probability and the cost is counted. In other words, in dynamic optical path networks, the utilization of the network resources is less than one. Under this assumption, we try to minimize the blocking of path connection requests.

As shown in Fig. 8, with the introduction of dynamic intermediate grooming, the normalized facility cost is substantially reduced for both the Establish-first (Est) and Grooming-first (Grm) algorithms compared to the end-to-

end (E2E) scheme. The E2E scheme, which always utilizes end-to-end direct wavebands, requires many more fibers since the direct waveband paths connecting each node pair are not always sufficiently utilized. Therefore, the network utilization is lower than the others and a higher network facility cost is required especially in the low traffic region. By introducing intermediate grooming, as in the Est and Grm schemes, network utilization is greatly enhanced and as a result the facility cost is reduced. It is found that for all the traffic intensities tested, from 1 to 9, the Est scheme outperforms the Grm scheme for the same waveband capacity.

Figure 9 shows the normalized signaling cost, where the signaling cost, introduced in Sect. 1, represents the average number of nodes that are involved in path setup/release operations needed for each connection set-up/release request. When a wavelength path is accommodated within an already existing direct waveband path, only the end-nodes of the waveband are involved in the set-up/release processing. If grooming is performed, a wavelength path is accommodated within concatenated waveband paths, and the intermediate nodes used for grooming are involved in addition to the end-nodes of the wavelength path. Otherwise, wavelength paths are accommodated within newly established waveband paths that directly connect the source/destination nodes of the wavelength paths. In this case, all the nodes on the routes of the waveband paths are involved and hence counted. The connection set-up/release delay is affected by the number of nodes involved in the operation. The numbers of nodes involved on several topologies are shown in Table 1. The required time depends on the operation network architectures and protocols. Distributed or more centralized architectures using the Path Computation Element (PCE) [27] can be used, which are outside the scope of this paper. Generally speaking, if waveband paths are not frequently managed, wavelength path set-up/release will become simple and fast. Therefore, for simplicity, the signaling cost in this study is evaluated based on the average number of nodes that are involved, as mentioned before. The signaling cost is confirmed to be reduced using the proposed approach for almost all cases compared to the single layer network. A reduction of greater than 50% is achieved if the traffic demand is greater than 2 for the 7 × 7 polygrid network as shown in

**Table 1** Average hop counts and expected minimum signaling cost ratio per wavelength connection for uniformly distributed demand.

		cost266	5x5	7x7	9x9
Single layer NW	Average hop counts	3	3.3	4.7	6
	Average No. of nodes involved in path operation	4	4.3	5.7	7
No. of nodes involved in wavelength path established via existing waveband path		2 (only source & destination nodes)			
signaling cost ratio calculated from above numbers		0.50	0.47	0.35	0.29

Fig. 9.

In terms of the signaling cost, the E2E scheme is the best while it requires the largest facility cost. By introducing grooming, the two algorithms, Est and Grm, greatly reduce the network facility cost at the expense of a slight increase in the signaling cost. Regarding the Grm scheme, a wavelength path tends to use multiple waveband paths and hence higher utilization of the already-existing waveband path is achieved, or usage of existing waveband paths is encouraged. As a result, existing waveband paths tend to remain longer and the ability to adapt to a changing wavelength path distribution can be impeded. The Est scheme encourages more frequent setup/release of waveband paths. Due to the enhanced adaptation of waveband paths, the Est scheme offers the lowest cost for a large traffic demand area. Based on these observations, the preferable algorithm among those considered here is the Est algorithm since the use of grooming is kept small while keeping facility cost sufficiently low.

### 5.2 Bandwidth Optimization

The normalized facility costs and the normalized signaling costs are strongly dependent on  $W$ , the waveband bandwidth, and they are represented in Figs. 10 and 11, respectively. The Est algorithm is used and the average traffic demand between each node pair is changed. For all the  $W$  values, the signaling cost is reduced more than 40% and the cost reduction is enhanced as traffic increases. The facility cost is also reduced except for  $D = 1$ , and the cost reduction is enhanced as traffic increases. This is because the coarse granular routing established by wavebands is more effective for large traffic demand. That is, waveband capacity is not well utilized if traffic demand is small; the cost of waveband introduction is not fully offset by the benefits gained. This trend is also seen in previous works on static designs for hierarchical optical path networks (for example, see [11]). An improvement of greater than 30% can be obtained when  $W = 16$  and  $D \geq 6$ . Regarding the facility cost, the cost becomes higher when  $W = 4$  because the port reduction effect is smaller. When  $W = 8$  and  $W = 16$ , almost the same costs are achieved for  $1 \leq D \leq 6$ . When  $D \geq 7$ ,  $W = 16$  attains the largest facility cost reduction. On the other hand, regarding the signaling cost,  $W = 16$  yields the highest for almost all cases. This is because the facility reduction for  $W = 16$  is achieved by frequent grooming, which attained better waveband utilization, but raised the signaling opera-

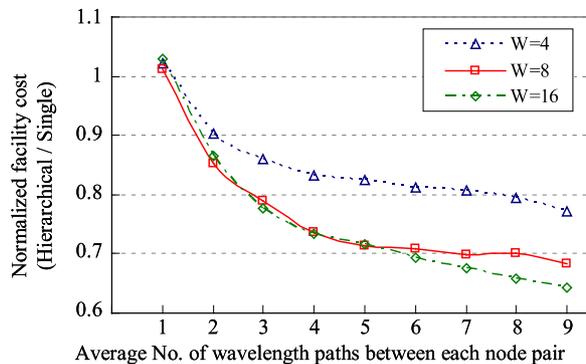


Fig. 10 Bandwidth optimization for facility cost in  $7 \times 7$  grid network.

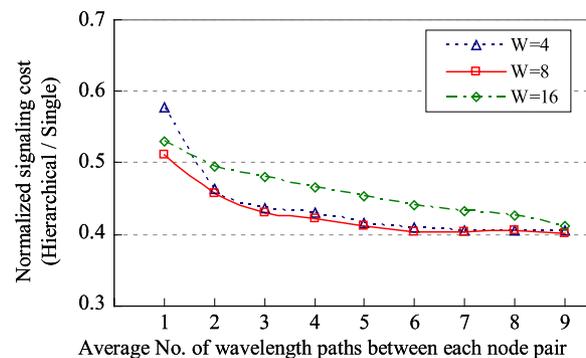


Fig. 11 Bandwidth optimization for signaling cost in  $7 \times 7$  grid network.

tion cost. Through the above observations, we conclude that for tested conditions in a  $7 \times 7$  network,  $W = 8$ , a medium-sized waveband is preferable since it can reduce the costs sufficiently and simultaneously.

### 5.3 Dependency on Network Size Variation

Figures 12 and 13 show the normalized facility costs and the normalized signaling costs, respectively, versus the average traffic demand between each node pair, where the network size and topology are changed. The normalized facility cost decreases as the network becomes larger. This is because the degree of cut-through of the WXC is enhanced as the average hop count becomes large, or the network size becomes large [11]. The normalized signaling cost reduction is also directly related to the network size. The average number of nodes involved in dynamic path operation in a single layer network is proportional to the averaged number of hops (see Table 1). On the other hand, in hierarchical networks, whenever a direct waveband with spare capacity exists, only the signaling processing at the end nodes is necessary. Therefore, a reduction of up to 50–71% is possible by utilizing the direct waveband tunnels (end-to-end wavebands) as shown in Table 1. The impact is enhanced as the network size increases. In practical situations as shown in Fig. 13, additional signaling is required since waveband path establish/release operations and grooming operations (traversing multiple waveband paths) exist. This slightly decreases the

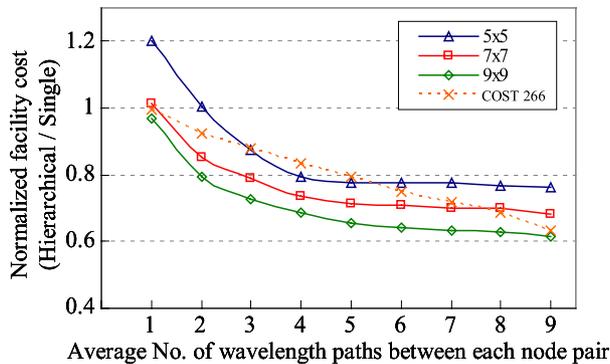


Fig. 12 Normalized facility cost variation for  $5 \times 5$ ,  $7 \times 7$ ,  $9 \times 9$ , and COST 266 networks.

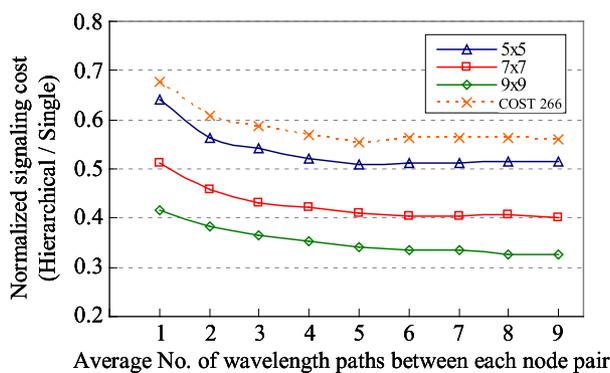


Fig. 13 Normalized signaling cost variation for  $5 \times 5$ ,  $7 \times 7$ ,  $9 \times 9$ , and COST 266 networks.

degree of reduction that is noted in Table 1. The similar discussions hold true regarding connection setup/release time. The total signaling time becomes longer when larger number of nodes is involved, and the time depends on the signaling scheme adopted. For example, in PSTNs (Public Switched Telephone Networks) where end-to-end connection setup is established switch by switch in a distributed manner, each subscriber and transit switch performs connection processing in series, which results in the total connection setup time of the sum of each switch setup time (plus signaling time). On the other hand, PCE (Path Computation Equipment) controls each switching node within each segment more in a centralized control manner, and then more parallel signaling processing and switch control may be done, however, to create a large scale network, multiple segment networks are necessary and coordination among the segments is necessary. In this environment, an example of signaling time dependency on node number is experimentally evaluated in [28], where signaling is based on GMPLS. For this case the signaling time was shown to be almost proportional to the node numbers traversed in a segment and also to the number of segment traversed. Thus reduction of connection setup time using waveband tunnel is substantial.

## 6. Conclusion

We proposed an optical fast circuit switching network architecture that introduces virtual mesh source and destination node connectivity actualized with waveband paths. We newly proposed dynamic waveband operation algorithms considering intermediate grooming. With the algorithms, waveband tunnels can be adaptively established/released as the wavelength path demand distribution changes. The setup/teardown operation of wavelength paths is significantly simplified by the waveband tunnels, and the operation cost is greatly reduced even though the waveband path operation is necessary. We also showed the importance of intermediate grooming in reducing the network facility cost. Numerical experiments showed that the network facility cost can be greatly reduced, at a slight operation cost increase, especially when the average number of wavelength paths between each node pair is small. The dependency of operation/signaling cost reduction on the network size was also clarified, and the cost reduction becomes more apparent as network becomes large. It was proved that by applying wavebands to create optical first circuit switching networks both facility and operation costs can be substantially reduced compared to single layer networks.

## Acknowledgments

This work was supported in part by the National Institute of Information and Communication Technology (NICT) and KAKENHI (23246072).

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**Appendix**

Network cost is the sum of the costs for nodes (BXC and WXC) and links (optical fiber and amplifier). The node/link costs are expressed as follows by using the given param-

**Table A·1** Parameters for cost evaluation.

Given parameters		
$C_{B\_NNI}$	BXC NNI (network node interface) port cost per waveband	1
$C_{B\_UNI}$	BXC UNI (user network interface) port cost per waveband	1.2
$C_{BXC}$	BXC base cost	4
$C_{W\_NNI}$	WXC NNI port cost per wavelength	1
$C_{W\_UNI}$	WXC UNI port cost per wavelength	1.2
$C_{WXC}$	WXC base cost	4
$C_F$	optical fiber cost per km	0.012
$C_{AMP}$	amplifier cost	2.04
$D_{AMP}$	amplifier span	60
$W$	maximum number of wavelength per waveband	
$B$	maximum number of waveband per fiber	
$K$	number of nodes in network	
$D_{ij}$	distance between node $i$ and node $j$ ; $D_{ij} = 0$ for node pair that is not physically adjacent to each other.	
Variables		
$F_{ij}$	number of fibers between node $i$ and node $j$	
$B\_NNI_i$	number of BXC NNI ports at node $i$	
$B\_UNI_i$	number of BXC UNI ports at node $i$	
$W\_NNI_i$	number of WXC NNI ports at node $i$	
$W\_UNI_i$	number of WXC UNI ports at node $i$	

ters and variables in Table A·1. The function also includes a constant that represents control systems and other overheads. Specific cost values used for the calculations are given in [11]. In the following, we show definitions of node and link cost functions for a K-node network.

**Node cost:**

$$C_{Node} = \sum_{i=1}^K \left( C_{B\_NNI} \times B\_NNI_i + C_{B\_UNI} \times B\_UNI_i + C_{BXC} + C_{W\_NNI} \times W\_NNI_i + C_{W\_UNI} \times W\_UNI_i + C_{WXC} \right)$$

**Link cost:**

$$C_{Link} = \sum_{i=1}^K \sum_{j=1}^K (C_{fiber}(i, j) \times F_{i,j})$$

with

$$C_{fiber}(i, j) = C_F \times D_{ij} + C_{AMP} \times \left[ \frac{D_{ij}}{D_{AMP}} \right]$$



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