An Efficient Hierarchical Optical Path Network Design Algorithm based on a Traffic Demand Expression in a Cartesian Product Space

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***Abstract*— We propose a hierarchical optical path network design algorithm. In order to efficiently accommodate wavelength paths in each waveband path, we define a source-destination Cartesian product space that allows the 'closeness' among wavelength paths to be assessed. By grouping 'close' wavelength paths, found by searching for clusters in the space, we iteratively create waveband paths that efficiently accommodate the wavelength paths. Numerical experiments demonstrate that the proposed algorithm offers lower total network cost than the conventional algorithms. The results also show that the hierarchical optical path network is effective even when traffic demand is relatively small.**

***Index Terms*— Waveband, hierarchical optical path network, Cartesian product space, network design algorithm, routing and wavelength assignment.**

I. Introduction

BROADBAND access including ADSL and FTTH is being rapidly adopted throughout the world. This has resulted in the rapid growth of Internet traffic. Current backbone networks mostly employ point-to-point WDM transmission systems and electrical forwarding and routing systems [1]. Therefore, they need OEO, optical to electrical and electrical to optical conversion, at every node. As the traffic volume continues to increase, electrical routing and OEO conversion will become a bottleneck and prevent the construction of cost-effective large bandwidth networks. In order to resolve this problem, a single-layer optical path network that employs wavelength routing by ROADM's and cross-connects [1, 2] has been introduced [3].

In the near future, the traffic increase will be greatly strengthened because of new broadband services including IP-TV and high definition TV. This traffic growth will result in an explosive demand in the switch size of the wavelength path cross-connect (WXC) and ROADMs. In order to keep node cost reasonable, the hierarchical optical path network [4] that employs the multi-granular optical path cross-connect (MG-OXC) was proposed [5, 6]. This cross-connect combines wavelength path cross-connection and waveband, a group of multiple wavelength paths, cross-connection. The effectiveness of the hierarchical optical path network has been investigated [7, 8]. In [7], the authors evaluated the efficiency of waveband switching compared to wavelength switching, and demonstrated its effectiveness as determined by the network and traffic conditions. In [8], the authors evaluated network cost in terms of the number of cross-connect switch ports and fibers and showed that they can be reduced by employing wavebands. Various node structures for the hierarchical optical path network are studied in [9], which demonstrated that switch size can be reduced by employing wavebands.

The hierarchical optical path network design task is an NP complete problem as the design of the single-layer optical path network [10]. In response, several heuristic or relaxation based algorithms were proposed [11–19]: they fall into three categories. The first group constructs wavelength paths first and then waveband paths are established [11–15]. In [11–13], wavelength paths having partially shared routes are groomed. The method in [14] accommodates wavelength paths within existing waveband paths. On the other hand, in [15], the authors proposed two greedy heuristics, one based on wavelength-path-first assignment and the other on waveband-path-first assignment, and showed that the former outperforms the latter. This kind of method is simple because it is almost equivalent to a well-accepted design method for single-layer optical path networks. However, further aggressive grooming is necessary to improve the waveband utilization ratio, especially when traffic demand is not large. Note has been made of the need to improve utilization ratios and to select a proper pair of route and waveband for each waveband path.

The second group constructs waveband paths first and then wavelength paths are accommodated into existing waveband paths [16–18]. In [16, 17], the traffic flowing into each node is defined as "potential" and employed as a criterion for setting up waveband paths. In [18], each waveband path is established so as to reduce the sum of hops between endpoints of the waveband path and wavelength paths. Further optimization of the placement of waveband paths can be done by setting an explicit relation between each waveband path and the wavelength paths to be accommodated. For example, restricting the hop increment of a wavelength path from its shortest hop and waveband path accommodation based on an exact estimation of cost suppression for each wavelength path in that waveband path will provide further cost reduction.

The third group covers relaxation-based methods [17, 19]. To reduce the computational complexity induced by integer linear programming formulation, the original problem is approximated by a combination of three subproblems [17], or

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the Lagrangean relaxation method is employed [19]. This approach is useful mainly for small networks where the sub-optimal solutions can be derived with a slight degree of relaxation, however, huge computational loads are generally incurred for large scale networks since the task is still a numerically hard problem. Because of the inherent difficulty of the design problem, instead of pursuing direct mathematical cost optimization, the iterative establishment of wavelength/waveband paths as the first and the second methods is practical to design large scale networks.

In this paper, we propose an algorithm that iteratively searches for groups of wavelength paths while, simultaneously, establishing waveband paths to accommodate them. Based on the observation that the goal is to maximize the cost reduction by cut-through WXC operation via waveband routing as well as to improve the utilization efficiency of each waveband, the proposed algorithm firstly defines a Cartesian product space in which 'nearby' traffic demands, as wavelength paths, are classified as clusters of points in the space. The proposed algorithm then iteratively identifies clusters and then, for each cluster, establishes a waveband path that accommodates the wavelength paths in the cluster. This procedure consists of simple operations and so supports large scale networks. The efficiency superiority of the proposed method over conventional methods is demonstrated through numerical experiments. We also discuss the cost reduction that can be attained by introducing hierarchical optical paths over single-layer optical path networks. Determination of waveband capacity, i.e. the maximum number of wavelength paths that can be accomodated within a waveband path, which depends on the traffic volume in the network will also be performed. A preliminary version of this paper was shown in an international conference [20].

II. Preliminaries

A. Hierarchical Optical Path Network

In the hierarchical optical path network, we assume the multi-granular optical cross-connect (MG-OXC) shown in Fig.1 that can process paths with different granularity: wavelength paths and waveband paths. This MG-OXC is divided into two parts. One part consists of the waveband cross-connect (BXC) and waveband multiplexer/demultiplexer for routing higher-order waveband paths, and the other part consists of the WXC and wavelength multiplexer/demultiplexer for routing lower-order wavelength paths. An alternative is the non-hierarchical MG-OXC configuration, which defines two independent path granularities [6, 8, 14, 21]. With this scheme wavelength paths and waveband paths are accommodated simultaneously in a fiber. Grooming of wavelength paths at intermediate OXCs is not done and, as a result, no interworking between wavelength path cross-connects and waveband cross-connects is required, which simplifies the switch architecture. However, if the traffic pattern or traffic volume changes, the optimum wavelength path and waveband configuration changes and as a result, the scheme's effectiveness decreases. Furthermore, the flexibility of the cross-connect switch is very limited since the ratio of the number of wavelength paths to that of waveband paths, both accommodated within a fiber, has

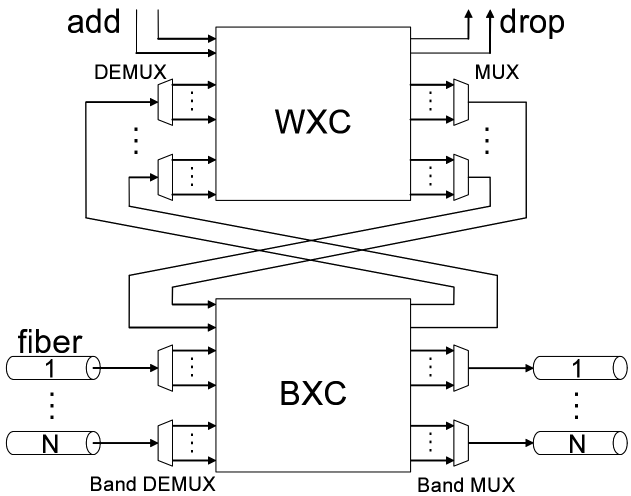

Fig. 1. Generic configuration of MG-OXC.

to be fixed to optimize the switch architecture. We, therefore, do not discuss this approach and employ the configuration shown in Fig.1. In this paper, we assume the absence of wavelength conversion to avoid the high cost of wavelength converters.

In the rest of this paper, we use symbols B and W to denote the number of wavebands in a fiber and the number of wavelengths in a waveband, respectively. Used wavelengths are properly labeled as $\lambda_1, \lambda_2, \ldots, \lambda_{BW}$ and the b th waveband $(1 \le b \le B)$ is a logically defined group of wavelength paths using $\mathrm{Band}_b := \{\lambda_k \,|\, k := (b-1)W + \{1, 2, \ldots, W\}\}$.

Suppose that H is the average number of hops in the network. Figure 2 is a simple example where W wavelength paths of H hops are accommodated and transported within a waveband path. In this arrangement, the total number of cross-connect switch ports used is $4W+2H+2$ whereas $2W(H+1)$ ports will be required in a conventional single-layer optical path network. In practical situations, given wavelength paths may not be enough to fulfill a waveband in general. For example, we need $2W+2H+2$ ports to carry $\frac{W}{2}$ wavelength paths by a direct waveband path. In this case, we can give a theoretical lower bound by $\frac{4W+2H+2}{W} \times \frac{W}{2} = 2W + H + 1 < 2W + 2H + 2$. Let $1/\alpha (0 \le \alpha \le 1)$ be the ratio of the number of ports required to accomodate all the path demands to those that can be attained when each wavelength path is accomodated within a direct waveband and all waveband usage rates are 1, i.e. theoretical bound. In the previous example, we have $\alpha = \frac{2W+H+1}{2W+2H+2} < 1$. The inefficiency of the accomodation can be represented by α. The ratio, R, of necessary ports between the hierarchical and conventional networks is given by

$$R = \frac{(4W+2H+2)/\alpha}{2W(H+1)} = \frac{1}{\alpha}\left(\frac{1}{W} + \frac{2}{H+1}\right).$$

Figure 3 shows the above relation among the ratio of port number R, the waveband capacity W, and the average number of hops H, for a hierarchical optical path network with $\alpha = 1$. The area where R is smaller than 1 is the effective area for introducing hierarchical optical paths when $\alpha = 1$.

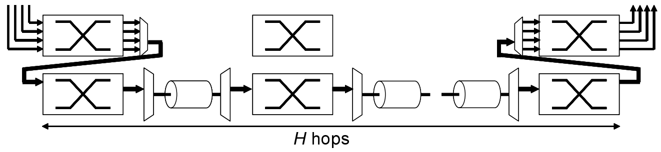

Fig. 2. Port occupation by an waveband in a hierarchical optical path network.

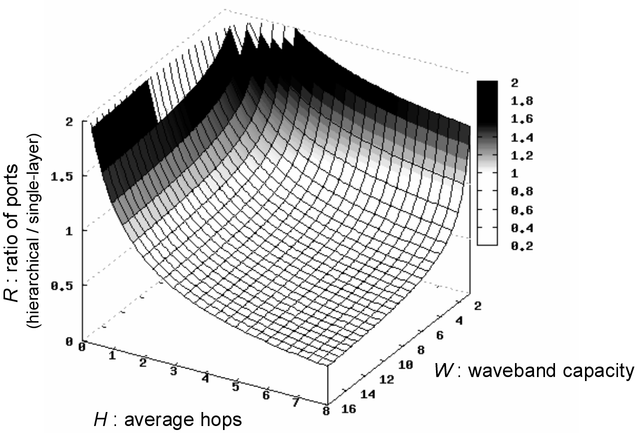

Fig. 3. Ratio of required optical ports: hierarchical to single-layer networks.

B. s-d Cartesian Product Space

Here we introduce and define the Cartesian product space. Let $\mathbb{R}$, $\mathbb{R}_+$ and $\mathbb{Z}_+$ be the sets of all real numbers, all nonnegative real numbers, and all nonnegative integers, respectively. Let $\|\cdot\|_p$ be the ℓ_p norm in the L-dimensional Euclidean space $\mathbb{R}^L$ defined by

$$\|(m_1,\ldots,m_L)\|_p := \begin{cases} \left(\sum_{\ell=1}^{L} |m_\ell|^p\right)^{1/p} & \text{if } 1 \le p < \infty \\ \max\{|m_1|,\ldots,|m_L|\} & \text{otherwise.} \end{cases}$$

Suppose that the given network can equivalently be expressed as the directed graph $G = (V, A)$ with K nodes, where $V = (v_k)_{k=1}^K$ is the vertex set that corresponds to all nodes in the network, and A is the arc set that corresponds to all links in the network. For each arc $a \in A$, from v_k to v_ℓ, its ends are respectively denoted by $\partial^+ a = v_k$ and $\partial^- a = v_\ell$. Each $(v_k, v_\ell) \in V^2$ is assigned to an nonnegative real number by $d : v^2 \to \mathbb{R}_+$, which denotes the distance between (v_k, v_ℓ).

Next we introduce a one to one relationship between the original vertexes and points in $\mathbb{R}^L$ so as to clearly define a metric between all node pairs. Define a bijectional mapping $f : V \to N := (\boldsymbol{n}_k)_{k=1}^K \subset \mathbb{R}^t (t \in \mathbb{Z}_+)$, which stands for the relationship, so that the distance between each node pair is $\|\boldsymbol{n}_k - \boldsymbol{n}_\ell\|_p = \|f(v_k) - f(v_\ell)\|_p \simeq d(v_k, v_\ell)$ and integer t is small enough (See Remark 1(1)). In most cases, the co-ordinate of point set N would be approximated by the geographical location, and $t = 2$ (See Remark 1(2)).

In this paper, we newly define a space $\mathbb{R}^t \times \mathbb{R}^t$ that is the Cartesian product of two spaces $\mathbb{R}^t$. We call this product space the "s-d (source-destination) Cartesian product space". For each traffic demand (= number of required wavelength paths) between source node v_k and destination node v_ℓ trf : $\mathbb{R}^t \times \mathbb{R}^t \to \mathbb{Z}_+$, we assign a co-ordinate in the s-d Cartesian product space where the co-ordinates of source node and

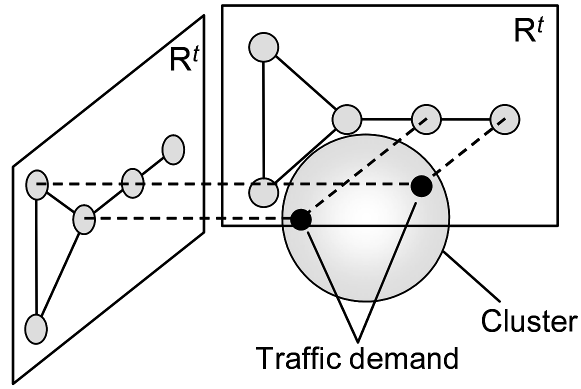

Fig. 4. Traffic demand expression in s-d Cartesian product space.

destination node are assigned to the co-ordinates of the first and second $\mathbb{R}^t$ space respectively. This yields the following integer-valued function dem : $\mathbb{R}^t \times \mathbb{R}^t \to \mathbb{Z}_+$ that represents traffic demand in the Cartesian product space $\mathbb{R}^t \times \mathbb{R}^t$

$$\mathrm{dem}(\boldsymbol{n}_k, \boldsymbol{n}_\ell) := \begin{cases} \mathrm{trf}(f^{-1}(\boldsymbol{n}_k), f^{-1}(\boldsymbol{n}_\ell)) & \text{if } \{\boldsymbol{n}_k, \boldsymbol{n}_\ell\} \subset N \\ 0 & \text{otherwise.} \end{cases}$$

Note that 'similar' traffic demands form a cluster of points as shown in Fig.4 which thus represent similar traffic demands. Let $\kappa(\geq 0)$ neighborhood $B_\kappa(\boldsymbol{n}_k, \boldsymbol{n}_\ell) := \{(\boldsymbol{n}'_k, \boldsymbol{n}'_\ell) \in N^2 \mid \|(\boldsymbol{n}_k, \boldsymbol{n}_\ell) - (\boldsymbol{n}'_k, \boldsymbol{n}'_\ell)\|_p \le \kappa\}$ in the s-d Cartesian product space (See Remark 1(3) for detail). We call κ the *radius* of $B_\kappa(\cdot,\cdot)$.

Remark 1:

1) The value of p will be selected to optimize the desired performance metrics. For example, ℓ_1 norm exactly stands for hop count in a regular polygrid topology, and ℓ_2 norm will approximate node distance for a general topology.
2) For large networks, for example Pan-European networks [22], the sphericity of the earth makes it difficult to define a planer approximation of G, which provides the smallest dimension and, therefore, is of most practical importance from the viewpoint of computational efficiency. In such a case, the sum of fiber distance/hops on each route would be an alternative to the distance measurement function.
3) The distance between two source/destination pairs $(\boldsymbol{n}_{s1}, \boldsymbol{n}_{d1})$ and $(\boldsymbol{n}_{s2}, \boldsymbol{n}_{d2})$ in the s-d Cartesian product space $\mathbb{R}^t \times \mathbb{R}^t$ is closely related to the distances between their source/destination nodes $\{\boldsymbol{n}_{s1}, \boldsymbol{n}_{s2}\}/\{\boldsymbol{n}_{d1}, \boldsymbol{n}_{d2}\}$. For example, for the typical values $p = 1, 2, \infty$,

$$\begin{aligned} \|(\boldsymbol{n}_{s1}, \boldsymbol{n}_{d1}) - (\boldsymbol{n}_{s2}, \boldsymbol{n}_{d2})\|_2^2 &= \|\boldsymbol{n}_{s1} - \boldsymbol{n}_{s2}\|_2^2 \\ &\quad + \|\boldsymbol{n}_{d1} - \boldsymbol{n}_{d2}\|_2^2 \\ \|(\boldsymbol{n}_{s1}, \boldsymbol{n}_{d1}) - (\boldsymbol{n}_{s2}, \boldsymbol{n}_{d2})\|_1 &= \|\boldsymbol{n}_{s1} - \boldsymbol{n}_{s2}\|_1 \\ &\quad + \|\boldsymbol{n}_{d1} - \boldsymbol{n}_{d2}\|_1 \\ \|(\boldsymbol{n}_{s1}, \boldsymbol{n}_{d1}) - (\boldsymbol{n}_{s2}, \boldsymbol{n}_{d2})\|_\infty &= \max\{\|\boldsymbol{n}_{s1} - \boldsymbol{n}_{s2}\|_\infty, \\ &\qquad \|\boldsymbol{n}_{d1} - \boldsymbol{n}_{d2}\|_\infty\}. \end{aligned}$$

Therefore restricting radius κ is directly related to the selection of wavelength paths that have close source/destination nodes and, therefore, the radius stands for the closeness between paths.

C. Cost Reduction by Each Wavelength Path

Let $\text{cost}_\lambda(v_k, v_\ell) \in \mathbb{R}_+$ be the cost of implementing a wavelength path between node v_k and v_ℓ where the path is accommodated within a series of sequentially connected 1-hop waveband paths between v_k and v_ℓ. Here we will assign one of the shortest paths between source and destination; such routes can be easily found by the well-known Dijkstra's algorithm [23].

Similarly, let $\text{cost}_{wb}(v_k, v_\ell; w_s, w_d) \in \mathbb{R}_+$ be the cost where the wavelength path is routed by BXC as a member of a waveband path directly connecting nodes w_s and w_d.

The cost functions $\text{cost}_\lambda(v_k, v_\ell)$ and $\text{cost}_{wb}(v_k, v_\ell; w_s, w_d)$ are evaluated as sums of costs of related hardware such as switch ports, amplifiers, and fibers. (The cost functions consist of many parameters and, therefore, we give them in Appendix I). We then have the following estimated cost reduction attained by WXC cut-through using waveband path.

$$\text{gain}(v_k, v_\ell; w_s, w_d) := \text{cost}_\lambda(v_k, v_\ell) - \text{cost}_{wb}(v_k, v_\ell; w_s, w_d)$$

III. Network Design Algorithm in s-d Cartesian Product Space

The goal of hierarchical optical path network design is to maximize the cost reduction attained by the cut-through permitted by WXC operation as well as to improve the utilization efficiency of each waveband. To achieve the former, the optical paths should be routed by using BXC and should be as long as possible. To achieve the latter, the spare capacity of each waveband path should be minimized. Unfortunately, without efficient intermediate grooming, these two strategies contradict each other when the traffic demand between node pairs is lower than the waveband capacity. The first strategy requires the establishment of a waveband path that directly connects the source and destination of each wavelength path. The second strategy requires the establishment of several, short, concatenated waveband paths to accommodate wavelength paths having different sources and destinations in order to maximize the utilization ratio of the waveband paths. Note that if the given traffic demand between each pair of nodes almost equals waveband capacity, direct waveband paths between nodes will also effectively satisfy the latter objective.

In order to simultaneously realize better cost reduction as well as higher utilization efficiency, we propose a design method that can effectively group wavelength paths that have neighboring sources and destinations. This can be done using the s-d Cartesian product space; a cluster in this space represents a set of similar traffic demands. Thus the proposed method searches for clusters in the space and creates waveband paths for the traffic demands, represented as points in the clusters, simultaneously. Figure 5 illustrates the accommodation of found wavelength paths. The long waveband path tends to have satisfactory levels of waveband occupancy without intermediate multiplexing/demultiplexing except at near by edges. Hereafter, we call the long waveband path the "main part", and the short waveband paths from/to the source/destination of wavelength paths the "edge parts" (see Figure 5).

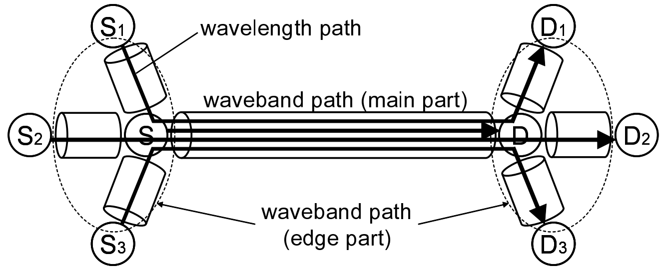

Fig. 5. Accommodation of similar wavelength paths to an waveband.

<Network design in s-d Cartesian product space>

Step 0. Parameter Selection

Define an s-d Cartesian product space after suitable selection of design parameters p, t, N. Determine radius $\kappa \geq 0$ that defines κ neighborhood, $\iota(\geq 0)$, the upper bound for the number of incremental hops in Step 1, and waveband construction threshold $X_{\text{wb}} \in (0, 1]$ that is the threshold for establishing a new waveband path in Step 2.

Step 1. Search for a Cluster

Let $S(\boldsymbol{n}_s, \boldsymbol{n}_d; \iota)$ be the set of all node pairs $(\boldsymbol{n}'_s, \boldsymbol{n}'_d)$ satisfying

$$\begin{aligned} &\text{hop}(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}_s)) + \text{hop}(f^{-1}(\boldsymbol{n}_s), f^{-1}(\boldsymbol{n}_d)) \\ &+\text{hop}(f^{-1}(\boldsymbol{n}_d), f^{-1}(\boldsymbol{n}'_d)) \\ \leq\ &\text{hop}(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}'_d)) + \iota \end{aligned}$$

where $\text{hop}(v_k, v_\ell)$ stands for the hop count of the shortest route between v_k and v_ℓ. (For details, see Remark 2). With descending order of $\|\boldsymbol{n}_s - \boldsymbol{n}_d\|_p$, search for a pair of points $(\boldsymbol{n}_s, \boldsymbol{n}_d) \in \mathbb{R}^t \times \mathbb{R}^t$ satisfying

$$\text{dem}(\boldsymbol{n}_s, \boldsymbol{n}_d) > 0$$

$$\sum_{(\boldsymbol{n}'_s, \boldsymbol{n}'_d) \in B_\kappa(\boldsymbol{n}_s, \boldsymbol{n}_d) \cap S(\boldsymbol{n}_s, \boldsymbol{n}_d; \iota)} \text{dem}(\boldsymbol{n}'_s, \boldsymbol{n}'_d) \geq X_{\text{wb}} W.$$

If such $(\boldsymbol{n}_s, \boldsymbol{n}_d)$ exists, select the one with the largest $\|\boldsymbol{n}_s - \boldsymbol{n}_d\|_p$ and go to Step 2. Otherwise, after all similar traffic demands have been accomodated by the scheme in Step 2, go to Step 3.

Step 2. Establishment of Waveband Paths

Step 2-1. Selection of Wavelength Paths to be Accommodated

For $B_\kappa(\boldsymbol{n}_s, \boldsymbol{n}_d)$ and $\text{dem}(\boldsymbol{n}'_s, \boldsymbol{n}'_d)$, define a set of wavelength paths to be accommodated, whose source-destination pairs $\nu \subset B_\kappa(\boldsymbol{n}_s, \boldsymbol{n}_d) \cap S(\boldsymbol{n}_s, \boldsymbol{n}_d; \iota)$ with $X_{\text{wb}} W \leq |\nu| \leq W$ such that

$$\text{ngain}(\nu) = \max_{\substack{\nu' \subset B_\kappa(\boldsymbol{n}_s, \boldsymbol{n}_d) \cap S(\boldsymbol{n}_s, \boldsymbol{n}_d; \iota) \\ X_{\text{wb}} W \leq |\nu'| \leq W}} \text{ngain}(\nu')$$

where

$$\text{ngain}(\nu') := \sum_{(\boldsymbol{n}'_s, \boldsymbol{n}'_d) \in \nu'} \frac{\text{gain}(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}'_d); f^{-1}(\boldsymbol{n}_s), f^{-1}(\boldsymbol{n}_d))}{\text{cost}_\lambda(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}'_d))}.$$

NOTE: Each co-ordinate may appear multiple times in ν so as to express the accommodation of wavelength paths with the same source/destination pairs.

Step 2-2. Routing of Wavelength Paths in the Edge Part
For the wavelength paths whose source-destination node pairs $(\boldsymbol{n}'_s, \boldsymbol{n}'_d)$ lie in ν, assign one of the shortest routes between $(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}_s))$ and $(f^{-1}(\boldsymbol{n}_d), f^{-1}(\boldsymbol{n}'_d))$.

Step 2-3. Weighting Function on a Multi-layer Graph
Define graphs G_b^{WaveBand} $(1 \le b \le B)$ for the b th waveband Band_b where G_b^{WaveBand} is equivalent to the original G except for the arc weighting. The weight $W_b : A \to \mathbb{R}_+$ is defined by

$$W_b(a) := \begin{cases} 2C_{\text{B\_NNI}} + \dfrac{C_{\text{fiber}}(\partial^+ a, \partial^- a)}{B} & \text{if all wavelengths in Band}_b \text{ are free in some fiber on the arc } a \\ (1+\Delta)\left\{2C_{\text{B\_NNI}} + \dfrac{C_{\text{fiber}}(\partial^+ a, \partial^- a)}{B}\right\} & \text{otherwise} \end{cases}$$

where $C_{\text{fiber}}(\cdot,\cdot)$ is defined in Appendix II and $\Delta \le \{\max_{v_k, v_\ell \in V} \text{hop}(v_k, v_\ell)\}^{-1}$ is introduced to encourage the use of existing fibers as much as possible while minimizing the hop count.

Step 2-4. Routing and Waveband Assignment
For each graph $G_b^{\text{WaveBand}}(b = 1, 2, \ldots, B)$, find one of the shortest paths between $(\boldsymbol{n}_s, \boldsymbol{n}_d)$ in Step 2-1 through Dijkstra's algorithm (if multiple routes are found, select one randomly). Let Wmain_b be the sum of weights on the shortest waveband path between $(\boldsymbol{n}_s, \boldsymbol{n}_d)$ on the G_b^{WaveBand}, and Wedge_b be a multiple of Δ multiplied by the total number of links, on which existing fiber does not have enough free wavelengths in Band_b, among the edge parts. at the main part and its edge parts. Find the minimizer b_{opt} where

$$\text{Weight}_b := \text{Wmain}_b + \text{Wedge}_b \ (b = 1, 2, \ldots, B)$$

and assign $\text{Band}_{b_{\text{opt}}}$ to the groups of wavelength paths in ν. For each link on the route of the main part, arbitrarily select one of the fibers that can accommodate $\text{Band}_{b_{\text{opt}}}$. If there is no such fiber, establish a new fiber in the link.

Step 2-5. Wavelength Assignment
In descending order of hop number $\text{hop}(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}'_d))$ $((\boldsymbol{n}'_s, \boldsymbol{n}'_d) \in \nu)$, assign a wavelength $\lambda_k \in \text{Band}_{b_{\text{opt}}}$, to a wavelength path connecting $\boldsymbol{n}'_s$ and $\boldsymbol{n}'_d$, that minimizes the number of links among the edge parts assuming no existing fiber can support λ_k. Arbitrarily select one of the fibers that can accommodate the wavelength path by using spare wavelengths of an existing waveband or by constructing a concatenated 1-hop waveband. If there is no such fiber, establish a new fiber in the link and construct a new 1-hop waveband on it. Go back to Step 1.

Step 3. Accommodation of Remaining Wavelength Paths

Step 3-1. Weighting Function on a Multi-layered Graph
Define a graph $G_k^\lambda = (V, A'_k)$, a modified version of G, for each wavelength λ_k $(1 \le k \le BW)$. In addition to the original links A, G_k^λ has additional links connecting (v_s, v_d) which stands for the waveband path connecting these nodes and has free capacity at λ_k. The weight $w_k^\lambda : A'_k \to \mathbb{R}_+$ is defined by

$$w_k^\lambda(a) := \begin{cases} 2C_{\text{W\_NNI}} & \text{if wavelength } \lambda \text{ is not used insome wavebands on the arc } a \\ 2(C_{\text{W\_NNI}} + C_{\text{B\_UNI}} + C_{\text{B\_NNI}}) & \text{else if wavelength } \lambda_k \text{ is not used in some fibers on the arc } a \\ 2(C_{\text{W\_NNI}} + C_{\text{B\_UNI}} + C_{\text{B\_NNI}}) + C_{\text{fiber}}(\delta^+ a, \delta^- a) & \text{otherwise} \end{cases}$$

so as to encourage the use of existing waveband paths and fibers as much as possible. Finally, we get a multi-layered graph as shown in Fig.6. The full lines represent the physical links, and the broken lines represent the virtual link that represents waveband paths with free wavelength λ_k.

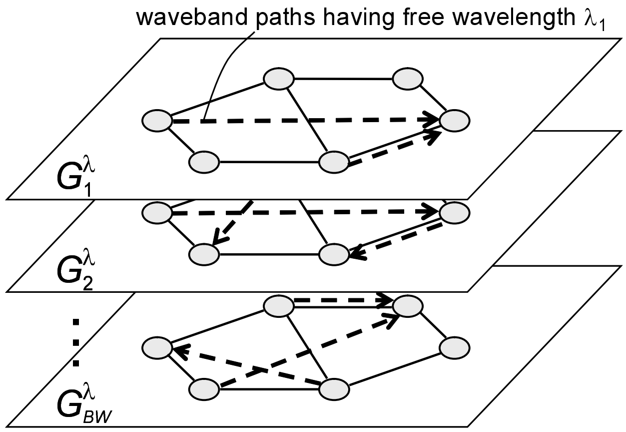

Fig. 6. Multi-layered graph indicating free capacity of waveband path

Step 3-2. Routing and Wavelength Assignment
For a demand that maximizes the hop number $\text{hop}(f^{-1}(\boldsymbol{n}'_s), f^{-1}(\boldsymbol{n}'_d))$ among remaining sets of all wavelength paths $\{(\boldsymbol{n}'_s, \boldsymbol{n}'_d)\}$, find one of the shortest paths in the graph G_k^λ $(k = 1, 2, \ldots, BW)$ by applying Dijkstra's algorithm to each graph.Select λ_k that minimizes the sums of weights on the shortest paths among all layers $(G_k^\lambda)_{k=1}^{BW}$. Establish a new fiber and 1-hop waveband on each link where necessary.
If remaining wavelength path demand still exists, repeat Step 3. Otherwise exit.

Remark 2: The proposed method has several parameters to be controlled. In addition to t and p for the s-d Cartesian product space discussed in Remark 1, the threshold X_{wb}, the radius κ and the hop increment bound ι must be set.

1) The selection of the radius κ and the threshold X_{wb} controls the ratio between the number of wavelength paths processed in Step 1 and 2 and that processed in Step 3. Smaller radius and higher threshold will realize better cost reduction if we have enough traffic demand whereas larger radius and lower threshold will be required for little traffic demand case. With exhaustive tests we found that $\kappa = 2$ provides the best result in our experiment. Regarding X_{wb}, the best value of X_{wb} depends on the amount of the traffic demand and the proposed method requires relatively short computation time (See Appendix III), all possible values are employed in our experiment.
2) In Step 1, the hop increment bound ι is introduced to suppress the cost increase occasioned by the extra ports. For a densely connected network, $\iota = 0$ will realize the lowest network cost. Indeed, we tried $\iota = 0, 1, 2$ for networks in the numerical experiments and found $\iota = 0$ to be the best choice.

Remark 3: The calculations are executed on a PC with a 2.8GHz AMD Opteron processor. The proposed method only requires 15–40 seconds to complete accommodation design for the 9×9 mesh network evaluated in Sec. IV-A. Evaluations of computational complexity are provided in Appendix III.

IV. Numerical Experiments

In this section, we employ the following parameters; $p = 1$ for polygrid networks, $p = 2$ for other networks, $t = 2$, and the hop increment bound $\iota = 0$. The cluster radius κ was set to a constant that was equivalent to 2 hops in ℓ_1 norm. The network cost was evaluated by a linear function of the total number of optical ports and total fiber length (See Appendix II). The proposed method was applied using all possible thresholds $X_{wb} \in \{1/W, 2/W, \dots, W/W\}$, and then one of the thresholds that minimized the function was selected. Finally, the obtained costs of the hierarchical optical path networks were normalized by those calculated for single-layer optical path networks. This procedure was repeated 20 times for each traffic demand and threshold X_{wb}; their ensemble averages were collected.

A. Comparison with Conventional Algorithms

In this simulation, we assumed the following conditions.

- Physical network topology: 9×9 polygrid network (link length 500km) and COST 266 pan-European network [22].
- Traffic demand: randomly assigned with uniform distribution equal probabilities among node pairs for polygrid network, and proportional to a multiple of populations at source and destination nodes for COST 266 network.
- Capacity of waveband: 8 wavelengths per waveband ($W = 8$).
- Capacity of fiber : 64 wavelengths per fiber (i.e. 8 wavebands per fiber ($B = 8$)).

For comparison, we also applied BPHT [13] and the end-to-end waveband scheme where the end-to-end waveband scheme

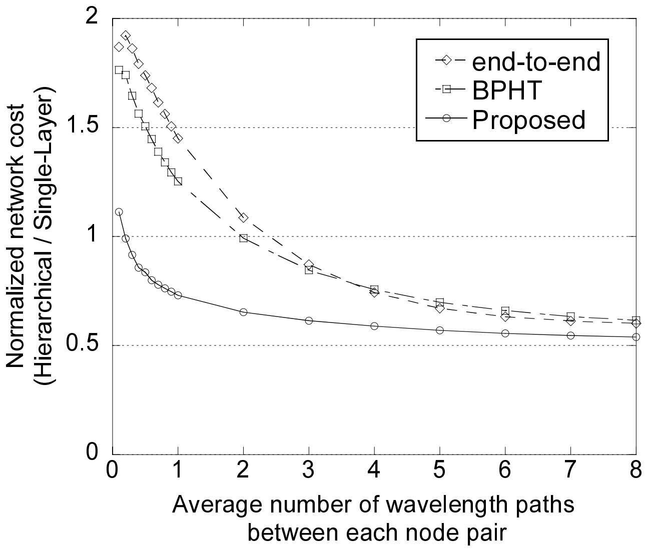

Fig. 7. Normalized network cost with proposed, BPHT, and end-to-end algorithm.

accommodates wavelength paths with the same source and destination into direct waveband paths between the node pairs.

1) 9×9 Polygrid Network: Figure 7 shows the normalized network costs obtained by the proposed algorithm, BPHT, and end-to-end scheme for the 9×9 network. This result shows that the proposed algorithm realizes 10-45% lower cost than the conventional ones at all traffic demands. If the amount of traffic demand is small, waveband utilization ratio will be low and the hierarchical optical path networks generally fail to realize cost reduction due to the increased complexity of the node architecture shown in Fig. 1. It is noted that even in the lower traffic demand range, i.e. number of wavelength paths is less than 2, the proposed algorithm offers much lower cost than the conventional ones. Except for the very small demand area, number of wavelength paths is less than 0.2, it is demonstrated that the hierarchical network is more cost effective than the conventional single-layer network.

Figure 8 shows the total number of necessary optical ports against the average number of wavelength paths demanded. As discussed in Sec. II-A, higher waveband utilization ratios and higher ratios of cut-through operations by BXC offer lower cost, however they often contradict each other. In this example the end-to-end pursues the maximization of the ratio of cut-through operation whereas BPHT aims at higher utilization ratios. As a result, when the load is 2 or 3, BPHT requires more ports than the end-to-end and less cost due to higher utilization ratio. The proposed method achieves not only lower cost but also fewer ports than the two methods for all traffic loads. The value of α represents the design efficiency, that is, the number of ports required to accomodate all the path demands to those that can be attained when each wavelength path is accomodated within a direct waveband and all waveband usage rates are 1 (See Section II-A). Comparison with Fig. 7 shows that the hierarchical optical path networks realize lower cost than the conventional single-layer optical path networks even in lower efficiency cases with $\alpha = 0.6, 0.8$. The proposed algorithm offers a design performance that is

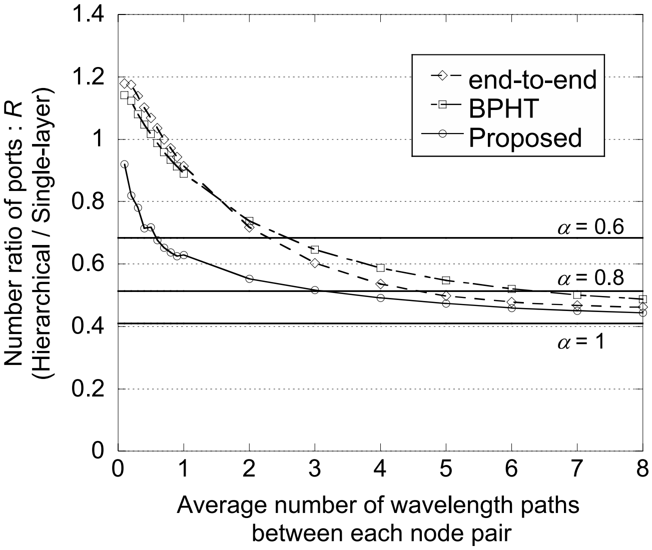

Fig. 8. The number ratio of ports with Proposed, BPHT, and end-to-end algorithm.

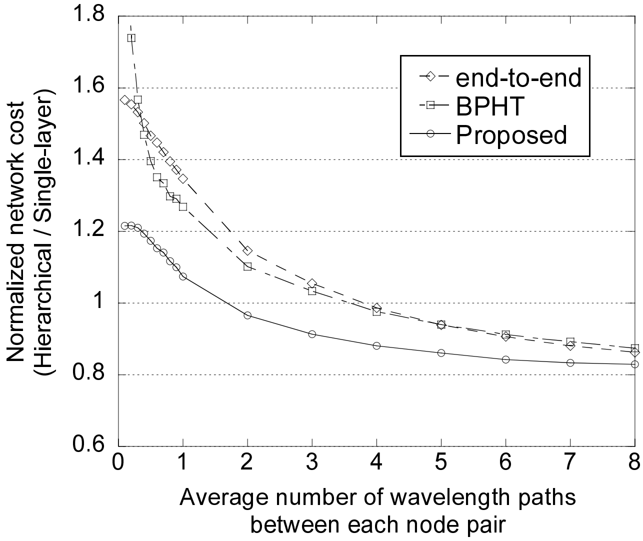

Fig. 10. Normalized network cost with proposed, BPHT, and end-to-end algorithm.

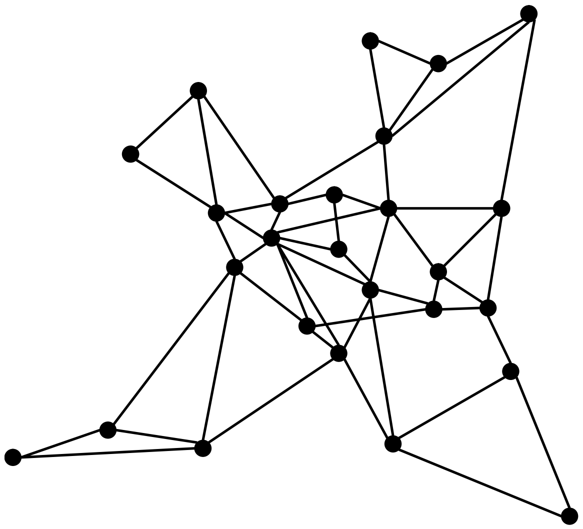

Fig. 9. COST 266 network topology for European photonic network.

closer to $\alpha = 1$, the theoretical bound, than the conventional algorithms. The proposed algorithm was shown to demand fewer ports than the conventional methods and, as a result, the total cost is reduced.

2) COST 266 Network: The COST 266 network is a European photonic network having 26 nodes and 51 links as shown in Fig. 9. Figure 10 provides the normalized network costs evaluated for this network. The proposed algorithm also realizes lower cost than the conventional ones at all traffic demands as in the polygrid network. Moreover, the hierarchical network is more cost effective than the single-layer network for wide range of traffic demands.

B. Sensitivity to Network Size

In this part, we assume the following network condition.

- Physical network topology: 5×5, 7×7, 9×9 polygrid network (link length 500km).
- Traffic demand: randomly assigned following uniform distribution.
- Capacity of waveband: 8 wavelengths per waveband (W=8).
- Capacity of fiber: 64 wavelengths per fiber (i.e. 8 wavebands per fiber (B=8)).

Figure 11 shows the normalized network costs versus the average traffic demand between nodes. The normalized cost decreases as the size of networks become large. This is because the ratio of the WXC cut-through is strongly related to the average hop count that is determined by network size as shown in Section II-A.

Figure 12 illustrates the ratio of necessary optical port number against the average hops between nodes for traffic demands, Dem, of 0.5, 1, 2, 4, 8. The vertical lines stand for the average hop numbers of wavelength paths for 5×5, 7×7, and 9×9 regular mesh networks, where the traffic distribution is random. The proposed algorithm achieves $\alpha \geq 0.6$ when the traffic demand is equal to or larger than 1, and $\alpha \geq 0.8$ when the demand is equal to or larger than 4. Furthermore, α is almost constant against the average hop number, that represents network size. This result demonstrates that the proposed method achieves stable cost reduction in diverse situations.

C. Waveband Capacity Optimization

In the hierarchical optical path network, waveband capacity, W, has a strong impact on the total number of optical ports needed, and as a result, on network cost. Generally speaking, smaller W offers smaller link cost while increasing node cost due to the higher utilization of wavebands and increased number of optical ports. The obvious question is; what is the value of W that minimizes the sum of link and node costs.

We assumed following network condition.

- Physical network topology: 5×5 polygrid network (link length 500km).

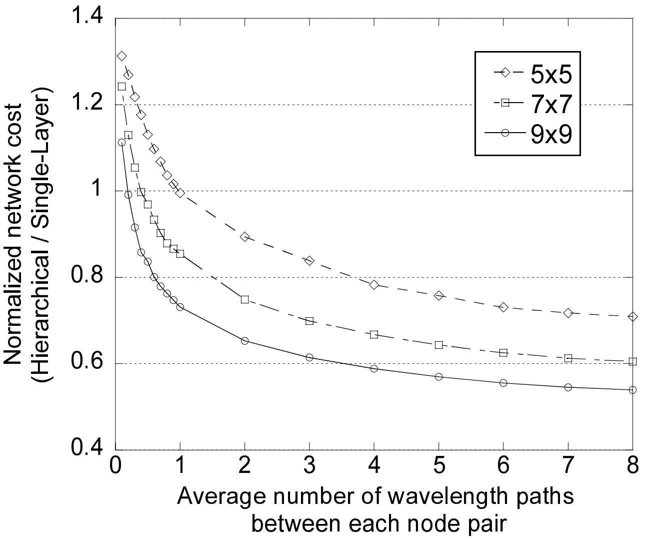

Fig. 11. Comparison of normalized network cost for 5×5, 7×7, 9×9 grid network.

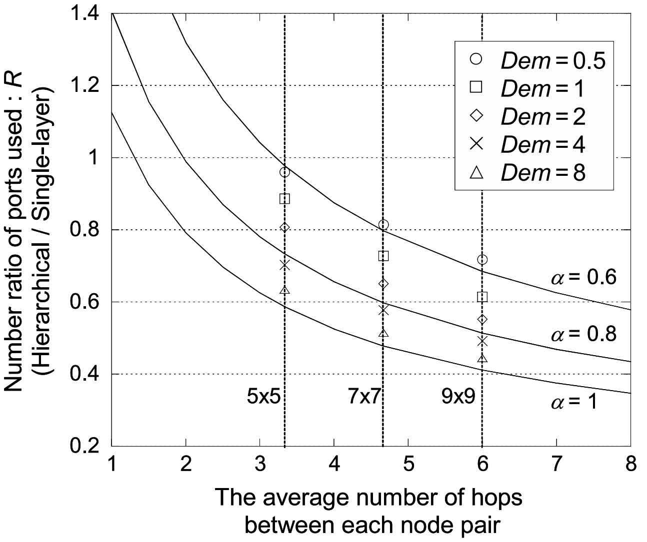

Fig. 12. Comparison of normalized port ratio for 5×5, 7×7, 9×9 grid network.

- Traffic demand: randomly assigned following uniform distribution.
- Capacity of fiber: 64 wavebands per fiber ($BW = 64$).

The normalized network costs with $W = 4, 8, 16, 32$ against the average traffic demand between each node pair are shown in Fig.13. The capacity $W = 4$ results in the worst cost because of poor port reduction, particularly when traffic demands are large. On the other hand, the reduction in network cost with $W = 32$ is insufficient because given traffic demand (less than 16 in Fig.13) is not enough to fill the huge waveband. When the traffic demand is less than 8, $W = 8$ provides the lowest cost because of lower link cost than W=16 whereas the node costs are almost equivalent. As the traffic demand increases above 8, the link cost with $W = 16$ approaches that with $W = 8$ due to the improvement in the utilization ratio of waveband paths while the node cost with $W = 16$ is smaller than that with $W = 8$. We can conclude that W

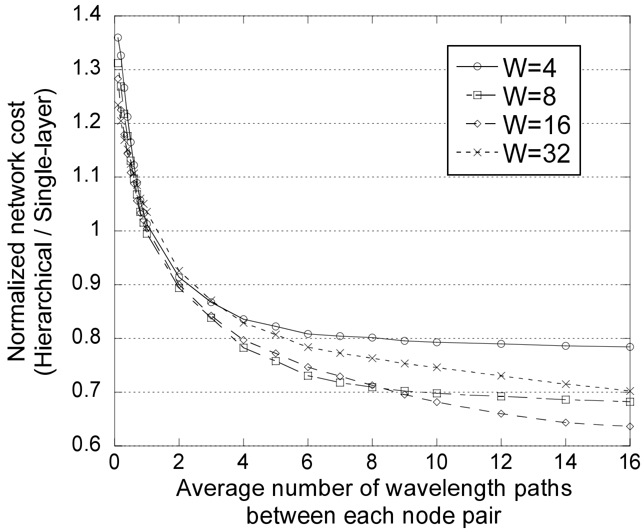

Fig. 13. Band optimization in 5×5 grid network.

should be large enough to offer some port reduction effect, and cost reduction is maximized when W is equal to or slightly larger than the given average traffic demand. For the limited area where the traffic demand is less than 1, the hierarchical optical path network can not reduce network cost compared to the single-layer optical path network.

V. Conclusion

In this paper, we proposed a new design algorithm for hierarchical optical path networks. We introduced the notion of the "s-d Cartesian product space"; it effectively enables the assessment of the 'closeness' of traffic demands and its utilization. By aggregating similar optical path demands and transferring on waveband paths, the proposed algorithm was proved to realize much lower network cost than that obtained not only by the conventional algorithms, but also by single-layer optical networks. The introduction of wavebands was shown to reduce optical switch size at cross-connects, which mitigates one of the major barriers to the implementation of large throughput optical cross-connect systems. The investigation given in this paper provides not only performance comparisons of different methods, but also clarifies the applicability region of the hierarchical optical path network. The hierarchical optical path network will be implemented in the not so distant future when traffic demand warrants it.

Appendix I

We give an estimation of the cost for realizing a connection between node pairs v_k to and v_ℓ. The connection cost of a wavelength path that is accommodated within concatenated 1-hop waveband paths is given by;

$$\begin{aligned}\mathrm{cost}_\lambda(v_k, v_\ell) :=& 2C_{\mathrm{W\_UNI}} + 2C_{\mathrm{W\_NNI}}\mathrm{hop}(v_k, v_\ell) \\ &+ \frac{2}{W}(C_{\mathrm{B\_UNI}} + C_{\mathrm{B\_NNI}})\mathrm{hop}(v_k, v_\ell)\end{aligned}$$

where factor $1/W$ is introduced because each waveband contains up to W wavelength paths; the other parameters are defined in Table I. On the other hand, the connection cost of a long waveband path from w_s to w_d and two short waveband paths each of which connects a pair of nodes (v_k, w_s) and (v_ℓ, w_d)(see Fig. 5), is given by

$$\begin{aligned}&\text{cost}_{wb}(v_k, v_\ell; w_s, w_d)\\ :=&2C_{\text{W\_UNI}} + 2C_{\text{W\_NNI}}(\text{hop}(v_k, w_s) + \text{hop}(v_\ell, w_d) + 1)\\ &+ \frac{2}{W}\big(C_{\text{B\_UNI}}(\text{hop}(v_k, w_s) + \text{hop}(v_\ell, w_d) + 1)\\ &+ C_{\text{B\_NNI}}(\text{hop}(v_k, w_s) + \text{hop}(w_s, w_d) + \text{hop}(v_\ell, w_d))\big).\end{aligned}$$

Appendix II

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 parameters and variables in Table I. The function also includes a constant that represents control systems and other overheads. Specific cost values used for the calculations are up-dated equivalents of the values given in [24].

Node cost:

$$\begin{aligned}C_{\text{Node}} := \sum_{i=1}^{K}(&C_{\text{B\_NNI}} \times \text{B\_NNI}_i + C_{\text{B\_UNI}} \times \text{B\_UNI}_i + C_{\text{BXC}}\\ &+ C_{\text{W\_NNI}} \times \text{W\_NNI}_i + C_{\text{W\_UNI}} \times \text{W\_UNI}_i + C_{\text{WXC}})\end{aligned}$$

Link cost:

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

with

$$C_{\text{fiber}}(i,j) := C_F \times D_{ij} + C_{\text{AMP}} \times \left\lfloor \frac{D_{ij}}{D_{\text{AMP}}} \right\rfloor$$

TABLE I
PARAMETERS FOR COST EVALUATION

Given parameters		
$C_{\text{B\_NNI}}$	BXC NNI (network node interface) port cost per waveband	1
$C_{\text{B\_UNI}}$	BXC UNI (user network interface) port cost per waveband	1.2
C_{BXC}	BXC base cost	4
$C_{\text{W\_NNI}}$	WXC NNI port cost per wavelength	1
$C_{\text{W\_UNI}}$	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	

Appendix III

In this appendix, the computational complexity of the proposed algorithm is evaluated.

1) Computational complexity of Step 1
Let the total number of given wavelength paths be #path. Maximum number S_C of search operations for the cluster is given by

$$\begin{aligned}&S_C\\ =&\frac{\text{“total number of given wavelength paths”}}{\text{“minimum number of paths in each cluster”}}\\ &\quad+\text{“number of node pairs”}\\ =&\frac{\#\text{path}}{X_{\text{wb}}W} + N(N-1).\end{aligned}$$

Then Step 2 is called once for each cluster. If uniformly distributed traffic demand is given, #path is proportional to the number of node pairs $N(N-1)$ and hence S_C is $O(N^2)$.

2) Computational complexity of Step 2
Dijkstra's algorithm is employed for route selection and computational cost for each operation is $O(N \log N)$. This cost is required for each cluster found in Step. 1, thus $O(N^3 \log N)$ operations are necessary in Step 1 and Step 2.

3) Computational complexity of Step 3
The maximum number of wavelength paths W_A that are not accommodated in Step 1 and 2 are estimated by

$$W_A = \frac{X_{\text{wb}W}}{\min \#B_\kappa} N(N-1)$$

where $\min \#B_\kappa$ stands for the minimum number of nodes in the cluster. For each wavelength path we apply Dijkstra's algorithm to find the optimal accommodation and it requires $O(N \log N)$ operations. As a whole, $O(N^3 \log N)$ operations are necessary in Step 3.

By the above discussion, we can conclude that the computational complexity, in terms of the number of nodes N, of the proposed algorithm is $O(N^3 \log N)$ when we have uniformly distributed traffic demand. Since the conventional algorithms consist of iterative application of Dijkstra's algorithm and the number of wavelength paths is proportional to the number of node pairs, the computational complexity of the proposed algorithm is essentially the same as that of the conventional algorithms.

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