An Algorithm for Waveband Routing and Wavelength Assignment in Hierarchical WDM Mesh Networks

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***Abstract*— Aggregation of wavelengths into wavebands is an attractive, cost-efficient way to facilitate switching and routing in optical networks. In this paper, we study the waveband routing and wavelength assignment (WRWA) tasks in hierarchical WDM mesh networks with optical crossconnects that can route multiple granularity (wavelengths and wavebands) at the same time. We solve the waveband routing and wavelength assignment sub-problems as a single problem, rather than separating them into two separate problems. We propose a waveband routing and wavelength assignment algorithm, which is designed to minimize the number of wavelength conversions. The algorithm is solved by using Dynamic Programming, sequentially on one lightpath request at a time. We comment on the WRWA performance under various traffic scenarios. Our results demonstrate a significant cost reduction compared to the WDM mesh networks with a single granularity, *i.e.*, without using wavebands.**

I. Introduction and Related Work

Wavelength division multiplexed (WDM) networks using wavelength routing by optical crossconnects (OXCs) [1] have emerged as the most feasible architectural solution for wide area backbone networks. The key enabling technology of Dense WDM (DWDM) is optical wavelength multiplexing and demultiplexing. The benefits of DWDM come at the expense of increased complexity of managing the wavelengths. Large numbers of available wavelengths result in increased complexity of OXCs and increased difficulty in implementing and maintaining OXCs. A way of reducing the complexity and size of OXCs is to group the wavelengths, thus creating a layered structure of optical paths. This is achieved by using a concept called wavebands, which was recently introduced in [2], [3]. A waveband consists of a group of several wavelengths and it is routed as a group through the optical switches. A waveband path occupies only two (input and output) ports of an optical switch in a node. The path hierarchy reduces node costs since a waveband can be switched optically as a single unit, thus reducing the number of expensive optical-electronic-optical (OEO) ports required for processing individual wavelengths. This, coupled with well designed routing and wavelength assignment algorithms may enable a cost-efficient implementation of optical networks.

The potential benefits of wavelength aggregation into wavebands was demonstrated in [3], [4]. Routing and wavelength assignment algorithms have been extensively studied in the general context of optical networking (see [1] and its references). The hierarchy of wavelengths and wavebands imposes new challenges to the routing and wavelength assignment problems in optical WDM mesh networks. In [4], [5], the authors proposed routing and path-aggregation algorithms and analyzed their performance by measuring the total cost of the ports used in the optical network. They also introduced a new functional device (non-uniform waveband de-aggregator) and demonstrated its advantages. A design method for wavelength routed networks employing a two-stage multiplexing scheme of waveband and wavelength is proposed in [6]. The authors presented an integer linear programming solution for the problem of waveband formation and routing. They also proposed a heuristic procedure as a practical method of designing general large-scale networks.

In general, the routing and wavelength assignment problem takes on two flavors: off-line and on-line [1]. In the off-line case, all lightpath requests are known in advance; thus a routing decision can be made based on the complete knowledge of the traffic to be served by the network. This case models new systems which must be populated according to an initial traffic matrix. In the on-line case, a lightpath request must be routed and wavelengths assigned independently of other lightpaths, which either have already been assigned or will be assigned in the future. Finding a globally optimal solution for the off-line problem is NP-hard. So one is forced to use algorithms which are sub-optimal but are computationally efficient for the off-line problem. The algorithm discussed in this paper can be used for both the off-line and the on-line versions. However, it is particularly well suited for the on-line version of the problem, which is the version that is of most interest from the point of view of a service provider.

The work presented in this paper differs from previous work in the following way: we solve the waveband routing and wavelength assignment problems as a single problem, rather than separating them into two separate problems. In our approach, we develop an optimal *sequential* dynamic programming formulation that minimizes the number of OEO

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ports used, which is the same as minimizing the number of wavelength conversions needed. By sequential, we mean one request is considered singly and sequentially, rather than all requests considered together. The algorithm finds the waveband paths and assigns wavelengths for all of the lightpath requests under consideration.

The rest of the paper is organized in the following manner. In the next section, we describe the main elements of hierarchical optical networking. In Section III we formally state the problem and in Section IV we present an algorithm for waveband routing and wavelength assignment. We present the results and discuss the performance of waveband routing and wavelength assignment algorithm in Section V. Conclusions are drawn in section VI.

II. Hierarchical Nodes and Networks

A waveband is a set of contiguous wavelengths, which are grouped together to facilitate low cost switching. A waveband path is a set of contiguous links on which all wavelengths constituting the waveband are switched as a group. This switching is done completely in the optical domain, thus reducing the number of wavelength conversions needed. In particular, when a waveband is switched, only two optical ports (input and output) of the switch are used and this reduces the number of expensive OEO ports needed. Any given connection request may use several of the waveband paths to satisfy its demand. An efficient way to route the request is to allow it to use one wavelength on each of the wavebands that it uses. Thus, when a request uses multiple waveband paths, wavelength conversion is needed only when the request is switched from one waveband to another. At these junction points, the expensive OEO ports are actually used.

The nodes in the optical network are hybrid optical devices each consisting of a waveband switch (transparent optical - OOO) and a wavelength switch (opaque OEO). The architecture of the hierarchical optical node (referred to as "hybrid cross-connect") with M input and output fibers and based on a single plane architecture is illustrated in Fig. 1. Each fiber carries K wavelengths (typical numbers are $K = 160$ and $K = 40$ for backbone and metro networks). Upon reaching the optical node, all K wavelengths in each input fiber are partitioned by waveband de-aggregators (WDAs) into P wavebands (each consisting of G wavelengths) where $K = PG$. The wavebands are optically switched and aggregated using waveband aggregators (WA) into output fibers by the optical core of the hierarchical node. The optical core may be realized by a single optical switch (Figure 1) or by P parallel optical switches, each of which handles the same waveband from all of the incoming fibers.

Contention for one output fiber among the same wavebands from different input fibers cannot be resolved in the transparent part of the device. The optical core also cannot process a waveband if different wavelengths within a waveband have to be switched into different output fibers. For these and other related tasks (such as adding a wavelength into a waveband), one or more wavebands have to be dropped to the OEO

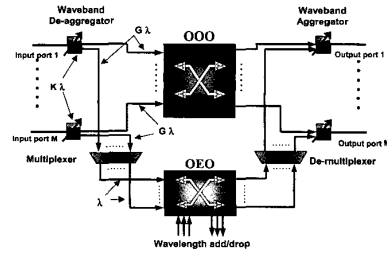

Fig. 1. Hierarchical Optical Node: Single Plane Architecture

part of the optical node. The OEO switch is equipped with multiplexers and de-multiplexers, each of them capable of processing a waveband consisting of G wavelengths. We are assuming that the OEO switch has κ (a power of 2) input and output ports with tunable lasers. The OEO switch also includes wavelength add/drop ports.

The OEO port is an expensive resource. Depending on the technology and the transmission speed, OEO ports could be between two and five times more expensive than optical ones. Thus the design of hierarchical optical node requires to take into account the impact of wavelength aggregation into wavebands. Specifically, the size G of waveband directly affects both the cost and performance of the node. On one hand, a small value of G creates a large number of wavebands which results in a large size of the optical core of the node. On the other hand, a large value of G increases the need for OEO conversion (large wavebands create more wavelength conflicts, as well as wavelength aggregation and de-aggregation overhead) which also creates the need for a large and expensive OEO part of the node.

In the rest of the paper we assume that all network nodes are hierarchical (homogenous model) so that a waveband path can be setup between any pair of nodes. Each waveband path, after it is set up, can carry a minimum of one wavelength and a maximum of G wavelengths between a specified pair of nodes. The waveband path traverses at least one link. The route of the multiple link waveband path includes two optical ports (input and output) of the OOO switch for each node it traverses. The origin of the waveband path is the waveband aggregator (WA) device (see Figure 1) located at the waveband's first link (output fiber), whereas its destination is the waveband de-aggregator (WDA) device (see Figure 1) at the waveband's last link (input fiber). Note that all wavelengths within the waveband path preserve their color throughout its journey since the waveband path does not pass through the OEO switch of any node along its route.

We now summarize the actions that can be performed on waveband paths:

(A) Adding a request from the output port of the OEO switch to the WA device:

- Adding a request using wavelength i to a non-existing waveband path sets up a new waveband path, which contains G wavelengths of which only wavelength i is being used at the time of the set up.

- A request using wavelength i can be added to a previously set up path if wavelength i is one of the G wavelengths comprising the waveband *and* it has not been used by any other request in that waveband path.
- Imagine that a waveband path has been set up (meaning that at least one request is using it) and assume that the waveband path starts at node a and terminates at node b. When a new request is added on wavelength i to this waveband path, the new request's point of entry can be on any of the nodes on the waveband's path (meaning that it does not necessarily have to be node a). However, the new request must terminate at node b, along with all other requests in that waveband path.

(B) Dropping a request from the WDA device to the input port of the OEO switch:

- Dropping any request using wavelength i automatically drops all wavelengths in the corresponding waveband path.
- When a waveband is dropped, only the wavelengths used in that waveband require OEO ports for termination. Unused wavelengths do not consume any wavelength conversion resources.

The WRWA problem is solved one request at a time, thus multiple requests between the same node pair are solved sequentially. The solution of a WRWA problem (one lightpath) includes the set of waveband paths and the wavelengths used along these paths. Each waveband path is in fact a virtual link comprised of one or more physical links. Since within each waveband path there is wavelength continuity, the number of OEO conversions per lightpath is equal to the number of waveband paths along the lightpath's route decreased by one. Our objective is to find a method which minimizes the number of wavelength conversions.

III. Problem Statement

A WDM mesh network of N nodes is modeled as an undirected graph (V, E), where $|V| = N$, and $|E| = J$. Nodes are labeled $0 \leq n \leq N-1$. A link (n, m) connects node n to node m. In this case, we assume that communication can take place from node n to node m or vice-versa on the link (n, m).

A wavelength set $\Lambda = \{0, 1, \cdots, K-1\}$ of size $|\Lambda| = K$ represents the wavelengths (also called colors) available in the WDM network. We assume that the wavelengths are aggregated into P wavebands u_p $(p = 0, \ldots, P-1)$ consisting of G wavelengths each. Each waveband consists of contiguous wavelengths, *i.e.*, the waveband u_p $(p = 0, \ldots, P-1)$ contains all the wavelengths with numbers from pG to $(p+1)G-1$. Note that $K = PG$.

We assume that at each node, the OEO switch has κ input and output ports with tunable lasers. We expect κ to be a power of 2. Any wavelength in the set Λ can be converted into any other, provided that the number of such conversions is limited to κ. The OEO switch also includes wavelength add and drop ports, but they are not counted as OEO ports. We assume that the size of the OOO switch at any node is large enough to switch wavebands from input fibers to output fibers without blocking. We also expect the cost of an optical port to be much smaller than the cost of an OEO port.

A request set $R = \{(s_0, d_0), \cdots, (s_{|R|-1}, d_{|R|-1})\}$ is defined as a set of pairs s_i and d_i, of size $|R|$, representing the source and destination nodes of the lightpaths to be provisioned. Note that $s_i \neq d_i$. The lightpath requests are unidirectional. A request for r lightpaths between a given pair of nodes is solved as r independent requests between the same pair of nodes.

The waveband path is a path on which all wavelengths of a waveband are optically switched together on the OO switches. A waveband path $w_p^{n,m}$ is defined as a path taken by the waveband u_p from the source n to the destination m. Thus, it can be viewed as a sequence of vertices $w_p^{n,m} = (n, I(1), I(2), \cdots, I(\ell), m)$, where $\{I(j); j = 1, \cdots, \ell\}$ represent the intermediate nodes in the waveband path. Note that two adjacent nodes in the waveband path must be connected by a valid link in E. Also, it is possible for ℓ to be zero. Corresponding to a waveband path $w_p^{n,m}$ is a waveband u_p, so a wavelength i belongs to waveband path $w_p^{n,m}$ if $i \in u_p$. A waveband path may be set up or not set up. A necessary condition for a waveband to be set up is that *at least* one wavelength from its band of G contiguous wavelengths is assigned to a particular request. If all of the wavelengths in a waveband are unassigned, then we say that the corresponding waveband path is not set up. Note that it is possible for a waveband path to contain one or more wavelengths that are not yet assigned. A waveband path represents a source node, intermediate nodes (if any) and a destination node and all wavelengths in the corresponding waveband travel on this path. In fact, a waveband path may be viewed as a virtual link between the source and destination nodes, which is comprised of several network links with capacity of G wavelengths. Color continuity within the waveband is preserved since the waveband traverses only optical switches at network nodes. Note that when waveband path $w_p^{n,m}$ is set up, it automatically implies that $w_p^{I(j),m} = (I(j), I(j+1), \cdots, I(\ell), m)$, for $j = 1, \ldots, \ell$ is also set up. This allows one request to use a particular wavelength on waveband path $w_p^{n,m}$ and another request to use a different wavelength on $w_p^{I(j),m}$. However, even when this kind of sharing happens, the two requests must both terminate at the common destination m.

A lightpath L_i for request i can now be defined as a sequence of j $(j \geq 1)$ concatenated waveband paths $L_i = (w_{p_1}^{n_0,n_1}, w_{p_2}^{n_1,n_2}, \cdots, w_{p_j}^{n_{j-1},n_j})$, where $n_0 = s_i$ and $n_j = d_i$. A node n_k, which is the destination node of waveband $w_{p_k}^{n_{k-1},n_k}$ and the source node of waveband $w_{p_{k+1}}^{n_k,n_{k+1}}$, must be capable of performing wavelength conversion. The color continuity is preserved within each waveband path, but wavelength conversion is needed when the lightpath is switched from the kth to the $(k+1)$th waveband path. Thus in the representation given above, the lightpath L_i uses one of the wavelengths of the waveband u_{p_k} when using waveband path $w_{p_k}^{n_{k-1},n_k}$ and perhaps a different wavelength from the waveband $u_{p_{k+1}}$ when using waveband path $w_{p_{k+1}}^{n_k,n_{k+1}}$. Note that switching a waveband through the OEO switch implies that all active wavelengths of the waveband are switched (see constraints A and B stated in Section II). Thus, in order to switch a waveband through the OEO switch, the number of available OEO ports (κ) must be greater than or equal to the number of active wavelengths in the waveband. The number of OEO conversions in the lightpath L_i is equal to $j-1$ (number of concatenated wavebands decreased by one). The WRWA problem has three goals. First, we need to determine the waveband paths to be used. Second, we want to assign the waveband paths to lightpaths corresponding to each request. Third, we need to assign appropriate wavelengths for each waveband path constituting a lightpath. We wish to perform these tasks in a way so as to minimize the number of OEO conversions, subject to satisfying the constraints spelled out earlier in this section.

The global optimization problem is NP-hard and therefore, we do not directly consider the global problem in this paper. Instead, we examine a class of algorithms with polynomial complexity, which are *sequential*. By sequential, we mean that the WRWA problem is solved one request at a time. Quite apart from the computational difficulty of coming up with a globally optimal solution, we state that the sequential optimization problem is more natural because in a real setting, we expect that requests will arrive one at a time and will have to be routed and assigned wavelengths one at a time. So our sequential algorithms are more suited for this purpose.

IV. Dynamic Programming Formulation

The problem described in Section III is quite complex. Despite this complexity, it is possible to come up with a dynamic programming formulation in which one request (at a time) is solved completely in terms of setting up appropriate wavebands and assigning wavelengths. However, the complexity of keeping track of the wavelength paths requires us to work with a redefined network, which has many more nodes and edges than the original network. This increase in state space is the price that one has to pay for solving the problem. Specifically, every node j in the original problem (except the source node of the request under consideration, which we call node 0) is actually replaced by a triple $[m,k,j]$. The meaning of a path from node 0 to node $[m,k,j]$ is that the lightpath travels from node 0 to node j ultimately, but in addition, the last link of the journey must be from node m to node j using wavelength k. Thus, in the description of the algorithm to follow, $f(0,k,j)$ is the cost of travelling directly (meaning no intermediate nodes) from node 0 to node j using color k. Similarly, $f(m,k,j)$ is the minimum cost of traveling from node 0 to node j, using color k on the last link, which is (m,j). Finally, in the algorithm to follow, $\Delta(m,k,n,\ell,j)$ is the one step cost of traveling from node $[m,k,n]$ to the node $[n,\ell,j]$ of the redefined network. In other words, it represents the cost of traveling on link (n,j) using wavelength ℓ in the original network, given that the lightpath had used link wavelength k on link (m,n), immediately prior to entering node n. Let us now illustrate this with an example. In the original network let a path traverse the nodes $(0,5,9,8)$ using wavelengths (1, 3, 4). Then in the redefined network, this path consists of traversing through the nodes (0, $[0,1,5]$, $[5,3,9]$, $[9,4,8]$). By using this enlarged state space, the node labels automatically take care of wavelength assignments and one can therefore use a dynamic programming algorithm as if the wavelength assignment part of the problem was not present. Note that the redefined network is much larger than the original network.

This algorithm performs the waveband path set-up and wavelength assignments simultaneously on one lightpath request at a time. The output of the WRWA algorithm is the lightpath consisting of a set of waveband paths (virtual links) and their assigned wavelengths. Note that the algorithm presented below is an optimal algorithm, (*i.e.*, the algorithm minimizes the number of wavelength conversions for one request at a time) and no approximations are involved, despite the complexity of the problem.

Step 1: For all $n,m \in V$ and $k \in \Lambda$ define $\alpha_{nm}(k)=1$, if wavelength k is available for use on that link, and 0 otherwise. Usually, $\alpha_{n,m}(k)=1$ for $k=0,\cdots,K-1$ and $(n,m)\in E$, unless for some reason, certain wavelengths are not available on some links. Also, if $(n,m)\notin E$, then $\alpha_{n,m}(k)=0$.

Associated with wavelength k ($k\in\Lambda$), there is unique number p_k ($p_k=0,\cdots,P-1$), such that $p_kG\le k\le(p_k+1)G-1$. For all $n,m\in V$ and $k\in\Lambda$, let $\beta_{n,m}(p_k)=1$ if link $(n,m)\in w_{p_k}^{a,b}$, where $w_{p_k}^{a,b}$ is a waveband path which has been set up between some source node a and destination b ($a,b\in V$). If there is no waveband path set up which uses link (n,m) and waveband u_p, then let $\beta_{n,m}(p_k)=0$. Initially, $\beta_{n,m}(p_k)=0$ for all $n,m\in V$ and $k\in\Lambda$. Similarly, for all $n,m\in V$ and $k\in\Lambda$ define $d_{n,m}(p_k)=-1$, if $\beta_{n,m}(p_k)=0$. Otherwise, if $\beta_{n,m}(p_k)=1$ and link $(n,m)\in w_{p_k}^{a,b}$, then set $d_{n,m}(p_k)=b$, where b is the destination node of the waveband path $w_{p_k}^{a,b}$. Initially, $d_{n,m}(p_k)=-1$ for all $n,m\in V$ and $k\in\Lambda$.

Let H denote the sum total of the hop count of all processed requests and let it be initialized to 0. Also, let C denote the sum total of the wavelength conversions of all processed requests and let it be initialized to 0. Let ϵ denote a small quantity satisfying $\epsilon<(KN)^{-1}$. This small quantity is added per hop to break ties between paths with the same number of OEO conversions. Thus if two paths have the same number of wavelength conversions, the path which requires the least number of waveband set-ups is preferred. For all $j\in V$, let $\mathcal{A}(j)$ be a subset of V containing nodes adjacent to node j, i.e., $n\in\mathcal{A}(j)$ if and only if $(n,j)\in E$. Set $\kappa_j=\kappa$ for all $j\in V$. Select the first request of the request set.

Step 2: Renumber the nodes of the network so that the source node of the request under consideration is numbered 0 and the destination node is numbered $N-1$. Since this renumbering is a permutation of the indices of the original network, permute the quantities $\alpha_{n,j}(k)$, κ_j, $\beta_{n,j}(p_k)$, $d_{n,j}(p_k)$, $w_{p_k}^{n,j}$ and $\mathcal{A}(j)$

in a similar manner, for all $n, j \in V$ and $k \in \Lambda$. Let the set $V^* = \{1, \cdots, N-1\}$, i.e., $V^* = V - \{0\}$. Let Z denote the set of all 3-tuples of the form (m, k, n) where $m \in V$, $n \in V^*$ and $k \in \Lambda$. Let Y denote a subset of Z and initialize Y to the empty set. For all $m \in V$, $j \in V^*$ and $k \in \Lambda$, let $\Theta(m, k, j) = 0$, $\Gamma(m, k, j) = 0$ and $\Pi(m, k, j) = 0$.

Step 3: Let $\wedge$ denote the "logical and" operation. Let us also define $f(m, k, j)$ as the current minimum cost of going from node 0 to node j and using wavelength k on link (m, j) at the end. Then, for all $j \in V^*$ and $k \in \Lambda$, we can initialize $f(0, k, j)$ as

$$f(0,k,j) = \begin{cases} \epsilon \text{ if } \alpha_{0,j}(k) = 1 \wedge \beta_{0,j}(p_k) = 0, \\ 0 \text{ if } \alpha_{0,j}(k) = 1 \wedge \beta_{0,j}(p_k) = 1 \wedge \\ \quad j = d_{0,j}(p_k), \\ 0 \text{ if } \alpha_{0,j}(k) = 1 \wedge \beta_{0,j}(p_k) = 1 \wedge \\ \quad j \neq d_{0,j}(p_k) \wedge j \neq N-1, \\ \infty \text{ otherwise.} \end{cases} \tag{1}$$

This initial value is equal to ϵ if the wavelength k is available and there is no waveband path $w_{p_k}^{a,b}$ $(a, b \in V)$ such that link $(0, j) \in w_{p_k}^{a,b}$. If the wavelength k is available and link $(0, j) \in w_{p_k}^{a,b}$ for some $a, b \in V$, the value of $f(0, k, j)$ is set to 0 in two cases. The first case is when node j is the same as node $d_{0,j}(p_k) = b$, i.e. $j = b$. The second case is when node j is neither node b $(j \neq b)$, nor node $N - 1$ $(j \neq N - 1)$, which represents the destination node of the lightpath under construction. For all $n \in V^*$, $m, j \in \mathcal{A}(n)$ and $k, l \in \Lambda$, let

$$\Delta(m,k,n,l,j) = \begin{cases} \epsilon \text{ if } k = l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 0 \wedge \beta_{n,j}(p_l) = 0, \\ 0 \text{ if } k = l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 1 \wedge \beta_{n,j}(p_l) = 1 \\ \quad \wedge d_{m,n}(p_k) = d_{n,j}(p_l), \\ 1+\epsilon \text{ if } k = l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 1 \wedge \beta_{n,j}(p_l) = 1 \\ \quad \wedge d_{m,n}(p_k) = n \wedge \kappa_n > 0, \\ 1+\epsilon \text{ if } k = l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 0 \wedge \beta_{n,j}(p_l) = 1 \\ \quad \wedge \kappa_n > 0, \\ 1+\epsilon \text{ if } k = l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 1 \wedge \beta_{n,j}(p_l) = 0 \\ \quad \wedge d_{m,n}(p_k) = n \wedge \kappa_n > 0, \\ 1+\epsilon \text{ if } k \neq l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 0 \wedge \kappa_n > 0, \\ 1+\epsilon \text{ if } k \neq l \wedge \alpha_{m,n}(k) = \alpha_{n,j}(l) = 1 \\ \quad \wedge \beta_{m,n}(p_k) = 1 \wedge d_{m,n}(p_k) = n \\ \quad \wedge \kappa_n > 0, \\ \infty \text{ otherwise.} \end{cases} \tag{2}$$

As explained before, $\Delta(m, k, n, l, j)$ in (2) represents the one step cost of going from node n to node j and using wavelength l subject to the condition that wavelength k was used on link (m, n). A cost of 1 above represents the fact that a wavelength conversion is needed at node n. Similarly a cost of ϵ represents the fact that a new waveband has to be set up as a result of the assignment. Finally, a cost of 0 indicates that the path can be set up using no color conversions on an already set up waveband path.

Step 4: Let

$$u = \min_{(m,k,j) \in Z-Y} f(m, k, j). \tag{3}$$

Let (ζ, ν, μ) be the value of (m, k, j) which minimizes (3). Resolve ties by first taking the lowest index of the j variable and if ties still remain, then the lowest index of the k variable. Let $Y \leftarrow Y \cup \{(\zeta, \nu, \mu)\}$. If $\mu = N - 1$ then go to step 5; otherwise continue. For all $j \in \mathcal{A}(\mu)$ and $k \in \Lambda$:

$$\begin{array}{l} \text{if } (f(\mu,k,j) > f(\zeta,\nu,\mu) + \Delta(\zeta,\nu,\mu,k,j) \;\; \text{then} \;\; \{ \\ \quad f(\mu,k,j) = f(\zeta,\nu,\mu) + \Delta(\zeta,\nu,\mu,k,j) \\ \quad \Pi(\mu,k,j) = \mu \\ \quad \Gamma(\mu,k,j) = \nu \\ \quad \Theta(\mu,k,j) = \zeta \\ \}. \end{array} \tag{4}$$

Repeat step 4.

Step 5: Let $\xi_0 = \mu$, $\phi_0 = \nu$, and $\rho_0 = \zeta$. If $f(\rho_0, \phi_0, \xi_0) = \infty$, stop. There is no path available for this request. Select the next request (if any left) from the request set and go to step 2. Otherwise, continue. Let $\xi_1 = \rho_0$, $\phi_1 = \Gamma(\rho_0, \phi_0, \xi_0)$, and $\rho_1 = \Theta(\rho_0, \phi_0, \xi_0)$. Then, initialize q to 1 and continue.

$$\begin{array}{l} \text{while } (\xi_q \neq 0) \;\; \{ \\ \quad q \leftarrow q+1 \\ \quad \xi_q = \Pi(\rho_{q-1}, \phi_{q-1}, \xi_{q-1}) \\ \quad \phi_q = \Gamma(\rho_{q-1}, \phi_{q-1}, \xi_{q-1}) \\ \quad \rho_q = \Theta(\rho_{q-1}, \phi_{q-1}, \xi_{q-1}) \\ \}. \end{array} \tag{5}$$

Step 6: Let $\alpha_{\xi_{j+1},\xi_j}(\phi_j) = \alpha_{\xi_{j+1},\xi_j}(\phi_j) - 1$ for $j = 0, \cdots, q-1$. Then, by using the following procedure, create wavebands, which are not already established, and update $d_{\xi_{j+1},\xi_j}(p_j)$ for $j = 0, \cdots, q-1$, where $p_j = \lfloor \phi_j / G \rfloor$.

$$\begin{array}{l} \text{for } (j = 0, 1, \cdots, q-1) \;\; \{ \\ \quad p_j = \lfloor \phi_j / G \rfloor \\ \quad \text{if } \;\; \beta_{\xi_{j+1},\xi_j}(p_j) = 0 \;\; \text{then} \;\; \{ \\ \qquad \text{if } \;\; j = 0 \;\; \text{then} \;\; \{ \\ \qquad\quad w_{p_j}^{\xi_{j+1},\xi_j} = \{\xi_{j+1}, \xi_j\} \\ \qquad\quad d_{\xi_{j+1},\xi_j}(p_j) = \xi_j \\ \qquad \} \text{ else } \;\; \text{if } \;\; \beta_{\xi_j,\xi_{j-1}}(p_{j-1}) = 0 \wedge \phi_j = \phi_{j-1} \;\; \{ \\ \qquad\quad d_{\xi_{j+1},\xi_j}(p_j) = d_{\xi_j,\xi_{j-1}}(p_{j-1}) \\ \qquad\quad w_{p_j}^{\xi_{j+1},\xi_\ell} = \xi_{j+1} \cup w_{p_{j-1}}^{\xi_j,\xi_\ell}, \;\; \text{where } \ell = d_{\xi_{j+1},\xi_j}(p_j) \\ \qquad \} \text{ else } \{ \\ \qquad\quad w_{p_j}^{\xi_{j+1},\xi_j} = \{\xi_{j+1}, \xi_j\} \\ \qquad\quad d_{\xi_{j+1},\xi_j}(p_j) = \xi_j \\ \qquad\quad C \leftarrow C+1 \\ \qquad\quad \kappa_j \leftarrow \kappa_j - 1 \\ \qquad \} \\ \quad \} \\ \}. \end{array} \tag{6}$$

Let $\beta_{\xi_{j+1},\xi_j}(p_j) = 1$ for $j = 0, \cdots, q-1$, where $p_j = \lfloor \phi_j / G \rfloor$, and $H \leftarrow H + q$. Pick a new request (if any left) from the request set and go to step 2.

Results: For the request under consideration, the optimal lightpath consists of $q+1$ nodes and equals $(\xi_q, \xi_{q-1}, \cdots, \xi_0)$, where $\xi_q = 0$ and $\xi_0 = N-1$. The wavelength used on the link (ξ_{i+1}, ξ_i) is ϕ_i for $i = 0, \cdots, q-1$. The total number of wavelength conversions of all processed requests is equal to C. This number is also equal to the sum of the number of concatenated wavebands decreased by one, for all the processed requests. At the end of step 5, the hop count for the request under consideration is given by q. The hop count of all requests processed so far is given by H. The value of κ_j for $j = 0, \cdots, N-1$ denotes the wavelength conversion capability still left at node j, after the processing of all requests so far. If $\kappa_j = 0$, then no wavelength conversion capability is left at node j. Note that κ_{ξ_0} and κ_{ξ_q} should not be decreased by one since the wavelength drop ports are not counted as OEO ports. The value of $\sum_{k \in \Lambda} \alpha_{n,m}(k)$ represents the total number of wavelengths left for use on the link (n,m) for all $n, m \in V$, after taking into account the wavelengths used by all requests processed so far. This method will minimize the number of wavelength conversions on one request at a time. If there are multiple ways in which this can be achieved, then it will minimize the number of waveband set-ups.

In step 4 we solve a shortest path problem from node 0 to the group of nodes of the form $[m, k, N-1]$ for $m \in V$ and $k \in \Lambda$ subject to waveband constraints A and B, given in Section II. Step 4 of the algorithm provides a dynamic programming formulation of this problem. Note that it is similar to (but not exactly identical to) the dynamic programming formulation that leads to the well-known Dijkstra algorithm. The only difference is that we are trying to find the shortest path from node 0 to a group of nodes rather than a single node. Readers unfamiliar with these details are referred to [7] or any other textbook containing an explanation of the dynamic programming formulation that leads to the Dijkstra algorithm.

In step 5 we describe how to recover the optimum decisions on waveband routing and wavelength assignment through backtracking. Step 6 describes the housekeeping functions which keep track of resources used and the consequent need for modifying the values of $\alpha_{n,j}(k)$, $\beta_{n,j}(p_k)$, $d_{n,j}(p_k)$, $w_{p_k}^{n,j}$, κ_j and H as a result of waveband routing and wavelength assignment of the current request.

V. Simulation Results and Performance Analysis

We implemented the waveband routing and wavelength assignment (WRWA) algorithm presented in the previous section in the form of a simulation tool. The simulator processes one lightpath request at a time, and attempts to find a route for a given request based on the WRWA algorithm. The output of the simulator is the provisioned lightpath, which is specified as a sequence of waveband paths and the associated wavelength assignments. The simulator keeps track of rejected lightpath requests, *i.e.*, those requests for which no lightpaths could be found.

We define two types of network nodes in the simulator. The first node type is called the OEO node and it represents an optical crossconnect (OXC) node that consists of the opaque OEO switch only. The second node type is called a hybrid node and it represents an OXC node that consists of both the waveband (transparent optical - OOO) and wavelength (opaque OEO) switch. We assume that the size of the OEO switch, namely κ, in the OEO node is larger than the size of the OEO switch in the hybrid node. All links in the simulator are assumed to be bidirectional.

In this paper, we compare the performance of the WRWA algorithm with the performance of a generic routing and wavelength assignment algorithm called *MinHop*. For each lightpath request the MinHop algorithm computes the shortest path between a source node and a destination node. We assume that in case of the MinHop algorithm, a network consists of OEO nodes only, whereas in case of the WRWA algorithm, a network consists of hybrid nodes only. The MinHop algorithm allocates only wavelength labels per link, since there is no notion of waveband path in networks with OEO nodes only. Note that the wavelength assignment problem in MinHop is trivial because each OEO node is assumed to have full wavelength conversion capability.

We use several performance metrics for comparison of two algorithms. The first one is the blocking probability, denoted as B, which expresses the ratio of the number of rejected lightpath requests to the total number of requests. The objective is to keep this number as low as possible. We expect to see a lower blocking probability under the MinHop algorithm due to full wavelength conversion capability in OEO nodes.

The second performance parameter is the average path length for all provisioned lightpaths, denoted as γ. Between two algorithms with the similar blocking probabilities, the one with "shorter" routes performs better since fewer network resources are occupied. The third and fourth performance parameters we are interested in are the actual number of OEO and OOO ports used, denoted as N_{OEO} and N_{OOO} respectively. We assume that an optical port costs c $(c < 1)$, while an OEO port has unit cost.

The total network cost is defined as the sum of costs of all OEO and OOO ports used. The costs of waveband aggregators, waveband de-aggregators, wavelength add and drop ports are not included in the total network cost. We expect the network cost under the MinHop algorithm to be greater than the network cost under the WRWA algorithm, because the MinHop algorithm uses much more of the expensive OEO ports. We define the fifth performance measure, namely the normalized network cost Ψ, as the ratio of the network cost under a given algorithm to the network cost under the MinHop algorithm. Its value is no grater than 1.

We simulated two network topologies. The first topology shown in Fig. 2 is the European optical network (EON), which consists of 85 nodes and 103 links. The second topology shown in Fig. 3 is American optical network (AON), which consists of 139 nodes and 154 links. All networks were assumed to be homogenous; in case of the MinHop algorithm, all nodes are of OEO type, and in case of the WRWA algorithm, all nodes are of hybrid type. Each link has capacity of 64 wavelengths in each direction. We also assume that the OEO and OOO switches have enough ports so that rejection of a lightpath request is a result of unavailable wavelengths on network links only. We assume that lightpath requests

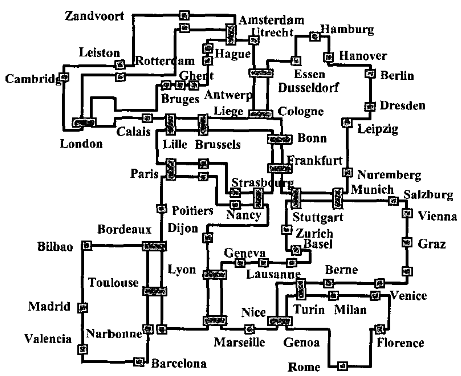

Fig. 2. European Optical Network

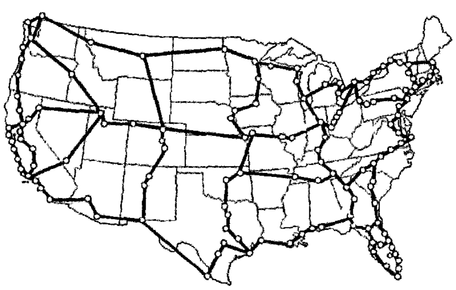

Fig. 3. American Optical Network

are unidirectional. For each network topology we simulated two traffic matrices, based on the uniform and Zipf [8] traffic distribution, respectively. In case of the uniform distribution, a source node and a destination node were randomly selected. In case of the Zipf distribution the nodes in the network were randomly ranked and the amount of traffic (integer number of wavelengths) destined for a particular node was set to be inversely proportional to its rank. A source node is then randomly selected for each request. The Zipf distribution is quite common in a wide variety of events (in particular, distribution of Web traffic among popular sites).

We carried out simulation runs for two network topologies (EON and AON), two traffic distributions (uniform and Zipf), different number of lightpath requests, and for the MinHop and WRWA algorithms. We simulated the following values of waveband granularity: $G = 2, 4, 8, 16$. In Tables, the waveband granularity $G = 1$ represents the MinHop algorithm. We also assume that the cost of one OOO port is 20% of the cost of one OEO port ($c = 0.2$). The results are described next.

We simulated different number of requests ($|\mathcal{R}| = 512, 1024, 1536$ and 2048) in case of the EON topology. The simulation results for the uniform distribution of traffic requests are shown in Table I. As this table shows, the blocking

TABLE I

WRWA Performance: Network - EON Traffic - Uniform

$\|\mathcal{R}\|$	G	B	γ	N_{OEO}	N_{OOO}	Ψ
512	1	0.00	8.22	7394	0	1.00
512	2	0.00	8.69	46	5712	0.16
512	4	0.00	9.25	324	3532	0.14
512	8	0.00	10.10	734	1960	0.15
512	16	0.00	10.53	1526	1024	0.23
1024	1	0.13	9.00	14234	0	1.00
1024	2	0.15	9.33	896	7820	0.17
1024	4	0.18	9.48	1444	4084	0.16
1024	8	0.19	9.49	2276	2072	0.19
1024	16	0.25	10.17	2846	1056	0.21
1536	1	0.31	8.12	15000	0	1.00
1536	2	0.33	8.56	1054	8102	0.18
1536	4	0.34	8.60	1736	4254	0.17
1536	8	0.36	8.92	2754	2136	0.21
1536	16	0.48	10.35	2596	1126	0.19
2048	1	0.46	7.71	14832	0	1.00
2048	2	0.47	8.06	970	7964	0.17
2048	4	0.48	8.33	1860	4208	0.18
2048	8	0.49	8.61	2854	2160	0.22
2048	16	0.55	10.07	3214	1116	0.23

probability under the MinHop algorithm ($G = 1$) is always less than that under the WRWA algorithm. Also, the blocking probability increases when the waveband granularity G is increased. In cases when $G = 2$ and $G = 4$, the blocking probability is very close to the value under the MinHop algorithm. On the other side, the normalized network cost is smallest when $G = 4$ or $G = 2$. As expected, the number of OEO ports used under the MinHop algorithm is significantly larger than that under the WRWA algorithm. This is the reason why the network cost is so high under the MinHop algorithm. Also, the number of OEO ports used is increased when the waveband granularity is increased since creation of larger waveband paths leads to more wavelength conversions due to less flexible routing for new requests. Obviously, the number of OOO ports used is reduced when the waveband granularity is increased. The average number of hops per processed request is smallest under the MinHop Algorithm, and increases when the waveband granularity is increased. If the overall performance of the algorithm is measured with respect to two performance measures: blocking probability and normalized network cost, then based on the simulation results in Table I, the WRWA algorithm with a waveband granularity of $G = 4$ has the best performance.

The simulation results in case of the EON topology and the Zipf distribution are shown in Table II. As this table shows, compared with the results for the uniform distribution, the blocking probability is higher for both algorithms. This result was expected since there are fewer destination nodes, with each of them receiving larger number of requests. The simulation results show that the WRWA algorithm with a

TABLE II

WRWA PERFORMANCE: NETWORK - EON TRAFFIC - ZIPF

$\|\mathcal{R}\|$	G	B	γ	N_{OEO}	N_{OOO}	Ψ
512	1	0.00	8.92	8108	0	1.00
512	2	0.00	9.18	44	5636	0.14
512	4	0.00	9.70	338	3384	0.13
512	8	0.00	10.39	818	1844	0.15
512	16	0.00	10.75	1440	998	0.20
1024	1	0.25	9.08	12474	0	1.00
1024	2	0.26	9.53	536	7076	0.16
1024	4	0.28	9.86	1224	3782	0.16
1024	8	0.30	10.27	1932	1992	0.19
1024	16	0.32	10.74	2444	1086	0.21
1536	1	0.42	8.47	13338	0	1.00
1536	2	0.44	8.92	642	7296	0.16
1536	4	0.44	9.22	1142	4030	0.15
1536	8	0.46	9.67	1818	2158	0.17
1536	16	0.49	10.16	2300	1108	0.19
2048	1	0.53	8.08	13724	0	1.00
2048	2	0.53	8.51	808	7588	0.17
2048	4	0.53	8.89	1560	4140	0.17
2048	8	0.55	9.00	2124	2098	0.19
2048	16	0.56	9.67	3036	1118	0.24

waveband granularity of $G = 4$ has the best performance.

We simulated different number of requests ($|\mathcal{R}| = 1024, 1536, 2048$ and 2560) in case of the AON topology. The results for both traffic distributions are presented in Table III and IV, respectively. They also show that the WRWA

TABLE III

WRWA PERFORMANCE: NETWORK - AON TRAFFIC - UNIFORM

$\|\mathcal{R}\|$	G	B	γ	N_{OEO}	N_{OOO}	Ψ
1024	1	0.09	13.08	22590	0	1.00
1024	2	0.09	13.68	1120	13050	0.17
1024	4	0.12	14.09	2052	6792	0.15
1024	8	0.15	14.34	2542	3554	0.14
1024	16	0.20	15.29	3128	1874	0.16
1536	1	0.29	11.81	23502	0	1.00
1536	2	0.31	12.42	1222	13186	0.16
1536	4	0.34	13.18	2220	7056	0.15
1536	8	0.37	13.46	2738	3720	0.15
1536	16	0.40	14.09	3418	1834	0.16
2048	1	0.41	11.42	25108	0	1.00
2048	2	0.42	11.69	1520	13432	0.17
2048	4	0.45	11.90	2198	7108	0.14
2048	8	0.48	12.95	2982	3688	0.15
2048	16	0.51	12.93	3980	1800	0.17
2560	1	0.51	11.21	25840	0	1.00
2560	2	0.51	11.67	1636	14098	0.17
2560	4	0.51	11.71	2554	7378	0.16
2560	8	0.55	12.77	3106	3846	0.15
2560	16	0.57	12.96	4106	1868	0.17

algorithm with a waveband granularity of $G = 4$ achieves a blocking probability slightly higher than the MinHop algorithm but at a significantly reduced network cost.

TABLE IV

WRWA PERFORMANCE: NETWORK - AON TRAFFIC - ZIPF

$\|\mathcal{R}\|$	G	B	γ	N_{OEO}	N_{OOO}	Ψ
1024	1	0.13	12.86	21116	0	1.00
1024	2	0.15	13.78	824	12302	0.16
1024	4	0.18	14.15	1412	6642	0.13
1024	8	0.24	15.01	1922	3522	0.12
1024	16	0.24	15.83	2694	1832	0.14
1536	1	0.35	12.72	23256	0	1.00
1536	2	0.36	12.82	1048	12642	0.15
1536	4	0.38	12.95	1644	6650	0.13
1536	8	0.42	14.03	2202	3602	0.13
1536	16	0.44	14.70	3150	1866	0.15
2048	1	0.48	12.01	23662	0	1.00
2048	2	0.48	12.30	1200	12958	0.16
2048	4	0.49	12.47	1782	6828	0.13
2048	8	0.50	12.42	2296	3594	0.13
2048	16	0.54	13.63	2896	1878	0.14
2560	1	0.55	11.70	24808	0	1.00
2560	2	0.55	12.03	1416	13386	0.16
2560	4	0.55	11.86	1822	7092	0.13
2560	8	0.56	11.98	2824	3662	0.14
2560	16	0.59	12.40	3208	1882	0.14

VI. CONCLUSION

In this paper, we studied the waveband routing and wavelength assignment (WRWA) tasks in hierarchical WDM mesh networks with optical crossconnects that can route multiple granularity (wavelengths and wavebands) at the same time. We solved the waveband routing and wavelength assignment sub-problems as a single problem, rather than separating them into two separate problems. We proposed a waveband routing and wavelength assignment algorithm, which is designed to minimize the number of wavelength conversions. Note that the algorithm presented is an optimal algorithm, using Dynamic Programming, and no approximations are involved, despite the complexity of the problem. Our results demonstrate a significant cost reduction compared to the WDM mesh networks with a single granularity, *i.e.*, without using wavebands. We plan to address more networks and traffic scenarios in our future work. We also plan to develop the off-line WRWA algorithm, which will be used when all lightpath requests are known in advance.

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