

A Systematic Wavelength Assign Algorithm for Multicast in WDM Networks with Sparse Conversion Nodes^{*}

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In this paper, we propose a systematic scheme of wavelength assignment for multicast in WDM network with sparse wavelength conversion nodes. The proposed scheme considers the generalized network environment when comparing to the literature [8], which assumed that all network nodes have no wavelength conversion capability. By using the concept of segmentation and grouping, the proposed scheme can be generally applied for the wavelength assignment of multicast in WDM network. Based on the foundation of the proposed scheme, three approaches, Minimum-Effect-First (MEF), First-fit, and Random, are provided for the selection of wavelength. The efficiency of the arrangement of wavelengths is measured by its influences on the available capacity of the network. The performance of the proposed scheme is examined through exhaustive simulations and compared with the upper bound. Our experimental results indicate that the proposed scheme can effectively minimize the affected bandwidth and the MEF approach is superior to the other two approaches.

Keywords: WDM, wavelength assignment, multicast, lightpath, effective network capacity

1. INTRODUCTION

In order to support the remarkable growth of network applications and services, the demand of network bandwidth has increased accordingly. The Wavelength Division Multiplexing (WDM) based network has been recognized as a convincing solution for the provisioning of broadband Internet [1, 2]. By transmitting many different wavelengths (channels) in the single fiber simultaneously, WDM provides wider bandwidth than does a traditional SDH network. In a WDM network, the Routing and Wavelength Assignment (RWA) is responsible for route decision and wavelength assignment of lightpath connections and is the most basic and important issue in resource management [10]. For the route decision, RWA should seek a suitable and proper path from the source node to the destination node. For the wavelength assignment, it should allocate an available and appropriate wavelength for the selected route to maximize the utilization of network resource. These two issues are very critical for the efficiency of network deployment. However, the complexity of solving the issues of routing and wavelength assignment at the same time is quite complex and is an NP-hard issue as mentioned in references [8]. And the issue of wavelength assignment is a more specific and significant issue in WDM networks. Hence we focus on this issue so that the affected bandwidth

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can be minimized. The wavelength assignment scheme shall be applicable for any routing algorithm. And the design of the proposed scheme also follows this concept.

The advent of high-speed multimedia applications, such as video streaming, HDTV programming and optical storage area networks, has made a dramatic increase in Internet traffic. For example, in order to increase the scalability, the service architecture of video on demand can be designed to separate the infrastructure into the WDM backbone and the access networks. The video programs are distributed over the WDM backbone through multicast, while the on-demand controls are managed by the access networks. Those applications need multicast to deliver information for multiple destinations simultaneously, so the capability of multicast in optical networks is an essential requirement toward broadband multimedia services. In [3], a wavelength routed optical network with tree architecture, named light-tree, was introduced. The light-tree can implement multicast transmission more effectively. Basically, a light-tree requires multicast-capable switch(es), which can split an incoming signal into n ($n \geq 2$) outgoing signals (split-and-deliver) and tap a fraction of the signal (tap-and-continue), for the achievement of multicast. In this paper, we assume that all nodes have the capability of multicast function, and the splitting loss is ignored. Although the use of a light-tree is helpful for multicast in a WDM network, it may not be possible to use a single wavelength to connect all destinations in the multicast tree without any converter because of the constraint of wavelength continuity. And the number of converters is always limited by cost considerations during the deployment. In this case, the multicast in a WDM network may comprise a set of lightpaths and light-trees.

The wavelength is one of the most important resources in a WDM network, and wavelength assignment is one of the main factors that affect the efficiency of the network utilization. Improper wavelength assignment, especially for the multicast connection, will cause wavelength blocking, whereas the network resources may be still underutilized. In this paper, we propose a novel scheme for wavelength assignment by considering network capacity. In order to assign wavelengths for a multicast request efficiently, the statistics of some potential request paths can be collected by the network management system. The network capacity is thought to minimize the block probability of potential request paths [4, 8]. The path capacity is defined as the available number of wavelengths from the source node to the destination node of the path. The wavelength continuity constraint, *i.e.*, that links from source to destination shall use the same wavelength to convey data in the same lightpath, always makes the wavelength assignment inflexible and causes wavelength blocking. As shown in Fig. 1, the capacity of the path from node 1 to 4 is 1 (λ_3). If there are two connection requests, (1, 3) and (1, 4), to be set up, a wavelength blocking occurs on path (1, 4) if λ_3 is assigned to path (1, 3). However, the blocking can be prevented by assigning λ_1 and λ_3 to paths (1, 3) and (1, 4), respectively.

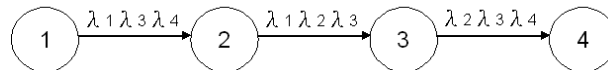


Fig. 1. Example of wavelength assignment.

In order to resolve the above issue, the wavelength converter is designed to reduce the constraint of wavelength continuity and then to increase the network utilization [5, 6].

Although the wavelength converter can maximize the available wavelengths for future usage, such a device is much more complex and expensive than that without conversion capability. Moreover, the signal may also decay during the conversion. Therefore, it is not possible to have all network nodes be equipped with wavelength conversion capability. A compromise approach is to deploy a portion of wavelength converters in the practical design of network architecture. The Sparse Wavelength Conversion Network (SWCN) is a WDM network with a limited number of wavelength conversion nodes. The study of resource arrangement in SWCN is very important for the deployment of WDM networks. In [7], placement strategies of wavelength converters and RWA were proposed. However, the multicast connections were not considered. In [8], a wavelength assignment scheme for multicast connection by maximization of the capacity of the network was proposed. All nodes considered in [8] were assumed to be without the capability of wavelength conversion. In this paper, we propose a new wavelength assignment scheme to be applicable for the multicast in the SWCN environment, which can be regarded as a kind of general architecture considered in [8]. The proposed Multicast Wavelength Assignment for Sparse Wavelength Conversion (MWA-SWC) can be regarded as the general scheme of Wavelength Assignment to Maximize the Network Capacity for Multicast (MWA-MNC) and can be applicable for the WDM networks with any number of wavelength converters.

This paper is organized as follows. The MWA-MNC scheme is briefly described in the following section. In section 3, the procedure of the proposed MWA-SWC scheme is described in a systematic manner and an illustrative example is also provided to assist in understanding the proposed scheme. The performance of the proposed scheme is examined and discussed through exhaustive simulations in section 4. Finally, the conclusions are provided in last section.

2. OVERVIEW OF WAVELENGTH ASSIGNMENTS FOR MULTICAST

The issues of wavelength assignment for multicast have been studied recently. Most of them focused on minimizing the number of wavelength conversions and wavelengths used [11-15]. In [11] and [14], all network nodes were assumed to be capable of conversion capability while, in [12] and [13], the network was assumed not to have any wavelength conversion node. Although the network with sparse wavelength conversion was discussed in [15], the main purpose of that reference was to minimize the number of wavelength conversions, and the issue of decreased capacity was not considered. The MWA-MNC schemes, proposed in [8], took the network state into consideration during wavelength assignment of a multicast tree. They consider not only the number of wavelengths used for a multicast tree, but also the impact of the potential network capacity. A multicast tree is assumed to be arranged under the constraint of the present network state, in which several potential request paths (represented by a traffic matrix) exist. Wavelengths are assigned to the multicast tree by consideration of the minimization of the influenced network capacity. It has been verified in [8] that the above issue is an NP-hard problem for a mesh based network topology. Therefore, the Static Cost Greedy (SCG) and Dynamic Cost Greedy (DCG) schemes, which are based on the cost ratio of wavelength, were proposed to solve this problem heuristically. Let N_k be the number of destinations

that can be reached in the multicast tree by using the wavelength λ_k , and C_k be the decrease in network capacity after the assignment of wavelength λ_k . Then the cost ratio of the wavelength, ϕ_k , is defined as C_k/N_k . In the SCG scheme, the cost ratios of each available wavelength of all destination nodes are required to be calculated only once before the assignment. However, in the DCG scheme, whenever a wavelength is assigned, the cost ratio of wavelength for the residual wavelengths of all destination nodes shall be calculated once again. In the SCG scheme, the cost ratio of each wavelength is calculated first, and all calculated cost ratios are arranged in increasing order. Then the wavelength with the minimal cost ratio is assigned to the route to all destinations that the wavelength can reach. The assignment of wavelength is an iterative procedure with respect to the increasing order of the cost ratios until all destination routes are assigned with a wavelength. Basically, the assignment procedure of the DCG scheme is very similar to that of the SCG. The main difference between DCG and SCG is that the cost ratios of nodal residual wavelengths in DCG are calculated once again whenever a wavelength has been assigned for a route. As the cost ratios are reevaluated after each assignment, the cost ratios can be more representative for the practical state of the network. Therefore, the performance of the DCG scheme is slightly better than that of the SCG; however, its computation complexity is greater accordingly. It is noted that both of the above schemes assume there is no wavelength converter within the entire network and, this constraint is removed in our scheme.

3. PROPOSED WAVELENGTH ASSIGNMENT SCHEME OF SWCN

In this paper, we consider the wavelength assignment issue for a multicast tree as discussed in previous section, however, the WDM network is assumed to be with sparse wavelength conversion nodes. Let s be the source node, D be the set of all destinations, and T be the link set formed with the shortest path of the source node to each destination. A multicast request, $r = \langle s, D, T \rangle$, is asked for wavelength assignment under the potential request matrix, P with $|P|$ paths. Wavelengths to be assigned for the multicast request are performed by considering that the influence of the potential paths is the least with respect to the network capacity [8]. Generally, the path capacity is not directly obtained by calculating the amount of available wavelengths of the path. The affect of the wavelength continuity constraint and the wavelength conversion shall be considered. For example, in Fig. 2, the capacity of path (1, 4) is 0 if every node has no wavelength conversion capability. However, if node 3 has this capability, its capacity will become 2, because λ_1 and λ_5 can be assigned for the links (1, 2) and (2, 3) and node 3 can convert them into other wavelengths in link (3, 4). For the network with potential request matrix P , we define the network capacity to be the sum of the capacities of all potential paths. Assignments of wavelengths for the multicast request are performed by requiring that the influence of the potential request paths be the least, *i.e.*, that the decrease in network capacity be the smallest.

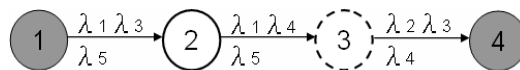


Fig. 2. Capacity of path with and without wavelength conversion.

In order to explain the proposed MWA-SWC scheme in a systematic manner, the procedure of the proposed algorithm is divided into the following three steps. The first step is the procedure of path segmentation and grouping, the second step is the calculation of network capacity, and the third step is the wavelength assignment by considering the affected capacity.

Step 1: Path segmentation and grouping

Generally, a multicast tree can also be treated as a collection of point to multiple-point paths from the source node to each destination node. For a path in the WDM network with sparse wavelength conversion nodes, each wavelength converter of the path can have the flexibility of choosing a suitable wavelength for its downlink. Then the main objective to minimize the affected capacity is to select a wavelength for the downlink of a converter node so that the influence on the potential request paths across it can be minimized. Thus, the wavelength conversion node can be regarded as an end point of a wavelength within a segment, and the path can be divided into “uni-wavelength” segments in accordance with the position of converters within the path. Therefore, we divide the paths, including paths from the source node to each of the destination nodes and the potential paths, into segments separated by the wavelength conversion nodes. The number of segments of path i will be $m_i + 1$ if there are m_i wavelength-conversion nodes being traveled by the path.

We define the set $D_i = \{d_i^1, d_i^2, \dots, d_i^j, \dots, d_i^{m_i+1}\}$ to represent all segments of the path from source to the i th destination (also named as path i) in the multicast tree. d_i^j is the j th segment of the path i . If $W_{d_i^j}$ is the set of available wavelengths of the j th segment of path i , then the number of wavelengths in $W_{d_i^j}$ is regarded as the capacity of this segment (notation is $|W_{d_i^j}|$). The capacity of the j th segment of the path i , $SC_{d_i^j}$ is obtained as

$$SC_{d_i^j} = \begin{cases} Overlap(s, c_i^k) = |W_{d_i^j}|, & k = 1, j = 1 \\ Overlap(c_i^{k-1}, c_i^k) = |W_{d_i^j}|, & 1 < k \leq m_i, j = k \\ Overlap(c_i^k, d_i) = |W_{d_i^j}|, & k = m_i, j = m_i + 1 \end{cases} \quad (1)$$

where s is the source node of the multicast tree; d_i is the i th destination of the multicast tree; and c_i^k is the k th wavelength converter in the path i . The function $Overlap(n_1, n_2)$ represents the size of the intersection set of all available wavelengths for all links from node n_1 to n_2 .

For the potential request paths considered in [8], we also define the set $P_i = \{p_i^1, p_i^2, \dots, p_i^{m_i+1}\}$ to indicate all segments of the i th potential request path, and the capacity of the j th segment of the potential path i , $SC_{p_i^j}$, can be stated as following

$$SC_{p_i^j} = \begin{cases} Overlap(s_i, c_i^k), & k = 1, j = 1 \\ Overlap(c_i^{k-1}, c_i^k), & 1 < k \leq m_i, j = k \\ Overlap(c_i^k, d_i), & k = m_i, j = m_i + 1 \end{cases} \quad (2)$$

where p_i^j is the j th segment of the potential path i ; s_i is the source node of the potential path i ; and d_i is the destination of the potential path i .

Basically, each segment can be treated as a reassignment domain of wavelength.

Segments of a path are mutually independent from the wavelength assignment point of view and may be with different segment capacities. The actual capacity of a path is basically determined by its segment(s) with the least capacity. The segment(s) with the least capacity of a path is named the critical segment of that path. Let PC_{d_i} and PC_{p_i} be the path capacity (the least segment capacity) of the path i of the multicast tree, and the path capacity of the potential path i , respectively. We have

$$PC_{d_i} = \min_{1 \leq j \leq m_j+1} SC_{d_i^j} \quad (3)$$

and

$$PC_{p_i} = \min_{1 \leq j \leq m_j+1} SC_{p_i^j}. \quad (4)$$

Thus, decreasing the capacity in a segment whose capacity is larger than the critical segment of that path will not decrease the capacity of the path. A path may have more than one critical segment. Let E_i , $E_i = \{e_i^1, e_i^2, \dots, e_i^u, \dots, e_i^{h_i}\}$, be the set of the critical segments in the potential path i and e_i^u be the u th critical segment of the potential path i . h_i is the number of critical segments in the potential path i . Then E_i can be regarded as the indicator to reflect whether the potential path is affected or not during the wavelength assignment of the multicast tree. Thus, if the segment traveled by the multicast tree is the critical segment of a potential path, the wavelength assignment of that segment will be carefully considered so that the impact on the potential path can be minimized. The concept of grouping is applied to couple segments which come from multicast tree with common links into groups. All segments within the group shall have common wavelengths. Thus, a group is composed of segments whose links are overlapped.

$$G = \{G_1, G_2, \dots, G_Z, \dots, G_Y\} \quad (5)$$

where G is the set of all groups in a multicast tree, G_Z is the set of all segments in the Z th group.

The multicast tree with n destinations can be treated as n unicast paths from source to each destination. Each path is segmented with respect to the wavelength converter. Segments of one group may have more than one common available wavelength. Let W_{G_Z} be the intersection set of all segments' available wavelengths in the Z th group. The group capacity, GC_Z , is defined as the number of wavelengths in W_{G_Z} . If links of a segment are overlapped with the links in the Z th group and there is no common available wavelength between them, this segment will be treated as a new group.

Step 2: Calculation of network capacity

The influence of network capacity is examined by checking whether the links of potential paths overlap with those of the multicast groups. If the overlap occurs at the critical segments of the potential path and the assigned wavelength is the one of the available wavelengths in that critical segment, the path capacity of the potential path will be affected. Let $C_Z(p_i, \lambda_j)$ be the capacity of p_i being influenced when the wavelength λ_j is assigned in the Z th group, and x be a common link of the Z th group and the critical segment of the potential path i . Then

$$C_Z(p_i, \lambda_f) = \begin{cases} 1 & \text{if } (\lambda_f \in x_w) \wedge x \in S_{Z,E_i} \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

where $S_{Z,E_i} = L_{G_Z} \cap L_{E_i}$, L_{G_Z} is the set of all links in the Z th group, L_{E_i} is the set of all links in the critical segments of the potential path i . and x_w is the set of all available wavelengths on link x .

The network capacity affected when λ_f is assigned for the Z th group, NC_{Z,λ_f} , can be obtained by the summation of the influence of all potential paths as

$$NC_{Z,\lambda_f} = \sum_{p_i \in P} C_Z(p_i, \lambda_f). \quad (7)$$

Since each group needs to assign one wavelength, the total network capacity affected, NC , can be obtained by the summation as

$$NC = \sum_{All\ Z} \sum_{p_i \in P} C_Z(p_i, \lambda_{Z,f}) - r \quad (8)$$

where $\lambda_{Z,f}$ is the wavelength assigned in the Z th group and r is the affected capacity that is counted repeatedly, which shall be regained, in the first term of Eq. (8). The repeated count happens when the same wavelength is assigned to the groups and the critical segment of path also travels through these groups. For example, the available wavelengths of the critical segment of potential path p_1 are (λ_1, λ_2) . G_1 and G_2 are the groups of the multicast tree. If λ_1 is assigned to G_1 and G_2 and if the critical segment of potential path p_1 travels through G_1 and G_2 , then, according to the first term of Eq. (8), the affected capacity of p_1 will be calculated twice. In fact, the decreased capacity is only one. The other repeated count happens when the same or a different wavelength is assigned to the groups and more than one critical segment of an individual path goes through these groups.

Step 3: Multicast wavelength assignment

As the multicast tree is separated into groups by conversion nodes, the wavelength assignments for groups are independent of each other. Thus, no matter which wavelength is assigned for the previous group, there will be no effect on the wavelength assigned in current group. Since all of the available wavelengths for a group have been collected in W_{G_Z} , the wavelength assigned for each group can be easily selected. If the cost or the affected capacity is not considered, the wavelength for each group can be selected as follows:

- First-Fit (FF) scheme: the wavelength of the minimum serial number in W_{G_Z} is assigned.
- Random (R) selection scheme: the wavelength is randomly chosen from W_{G_Z} .

In order to maximize the network capacity, the minimum-effect-first (MEF) approach is proposed to select the wavelengths for groups. The concept of MEF is that the wavelength, which has the least influence on the potential paths, is selected for that group. The affected network capacity derived in Eq. (7) is used to examine the influence for each wavelength assignment. The algorithm of MEF is illustrated in Fig. 3.

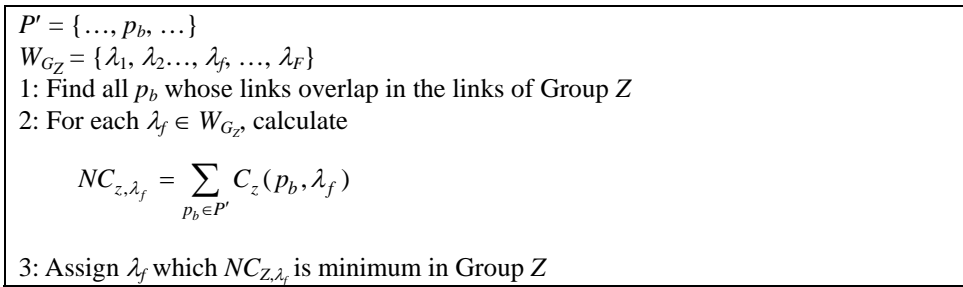


Fig. 3. Algorithm of MEF.

To analyze the complexity of the proposed scheme, we assume that there are N nodes in the network, where, among them, C nodes have the capability of wavelength conversion, each link has W wavelengths, and $|D|$ destinations are desired for the multicast tree. In the worst case, a multicast tree consists of $|D|$ paths, and each path has $(N - 1)$ links. Therefore, the complexity of step 1 is $O(NW |D|)$. For step 2, in accordance with Eq. (7), NC_{z, λ_f} needs to be calculated for each wavelength within one group, and all groups shall be examined. Then the time complexity of this step is $O(CW |P| N)$. In the last step, all groups must be assigned one wavelength according to the increasing order of NC_{z, λ_f} to reach all destinations. The complexity of the last step is $O(CW \log W)$. As the above three steps are performed sequentially, the complexity of the proposed algorithm is the highest one, which depends on the values of C , W , $|P|$, and N , of these three steps.

An example shown in Fig. 4 is provided to explain the operations of the proposed algorithm. It shows that a multicast tree, $\langle 2, \{9, 10, 14, 17, 18\} \rangle$, is established for wavelength assignment under the assumption of five potential paths as $p_1 \langle 3, 7 \rangle$, $p_2 \langle 0, 13 \rangle$, $p_3 \langle 3, 0 \rangle$, $p_4 \langle 11, 14 \rangle$, and $p_5 \langle 12, 2 \rangle$. Nodes 4, 5, 13, and 17 have the capability of wavelength conversion, whereas other nodes do not. The available wavelengths of each link are shown beside the link.

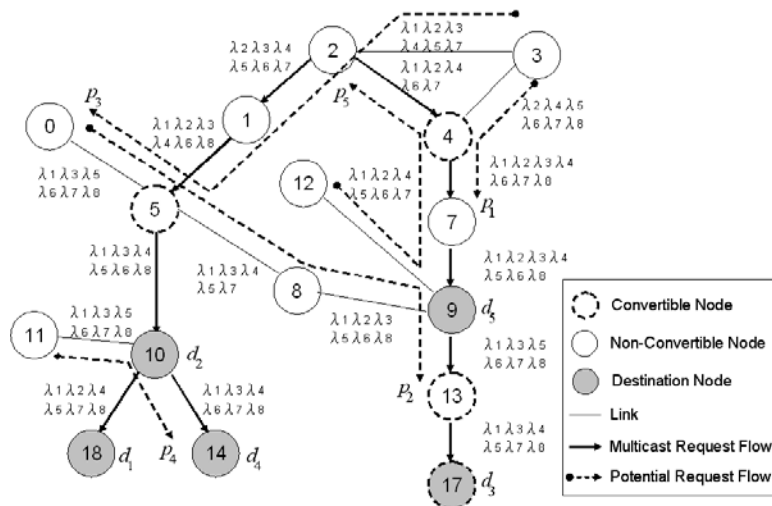


Fig. 4. An example of the proposed algorithm's operations.

The segment capacities of paths, derived from the multicast request and the potential traffic, can be obtained through Eqs. (1) and (2) in according with step 1 as follows:

$$\begin{aligned}
 W_{d_1^1} &= \{\lambda_2, \lambda_3, \lambda_4, \lambda_6\}, SC_{d_1^1} = 4 & W_{d_1^2} &= \{\lambda_1, \lambda_4, \lambda_5, \lambda_8\}, SC_{d_1^2} = 4 \\
 W_{d_2^1} &= \{\lambda_2, \lambda_3, \lambda_4, \lambda_6\}, SC_{d_2^1} = 4 & W_{d_2^2} &= \{\lambda_1, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_8\}, SC_{d_2^2} = 6 \\
 W_{d_3^1} &= \{\lambda_1, \lambda_2, \lambda_4, \lambda_6, \lambda_7\}, SC_{d_3^1} = 5 & W_{d_3^2} &= \{\lambda_1, \lambda_3, \lambda_6, \lambda_8\}, SC_{d_3^2} = 4 \\
 W_{d_3^3} &= \{\lambda_1, \lambda_3, \lambda_4, \lambda_5, \lambda_7, \lambda_8\}, SC_{d_3^3} = 6 & & \\
 W_{d_4^1} &= \{\lambda_1, \lambda_3, \lambda_4, \lambda_6\}, SC_{d_4^1} = 4 & W_{d_4^2} &= \{\lambda_1, \lambda_3, \lambda_4, \lambda_6, \lambda_8\}, SC_{d_4^2} = 5 \\
 W_{d_5^1} &= \{\lambda_1, \lambda_2, \lambda_4, \lambda_6, \lambda_7\}, SC_{d_5^1} = 5 & W_{d_5^2} &= \{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_6, \lambda_8\}, SC_{d_5^2} = 6 \\
 W_{p_1^1} &= \{\lambda_1, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8\}, SC_{p_1^1} = 6 & W_{p_1^2} &= \{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8\}, SC_{p_1^2} = 7 \\
 W_{p_2^1} &= \{\lambda_1, \lambda_3, \lambda_5, \lambda_6, \lambda_7, \lambda_8\}, SC_{p_2^1} = 6 & W_{p_2^2} &= \{\lambda_1, \lambda_3, \lambda_5\}, SC_{p_2^2} = 3 \\
 W_{p_3^1} &= \{\lambda_2, \lambda_3, \lambda_4\}, SC_{p_3^1} = 3 & W_{p_3^2} &= \{\lambda_1, \lambda_3, \lambda_5, \lambda_6, \lambda_7, \lambda_8\}, SC_{p_3^2} = 6 \\
 W_{p_4^1} &= \{\lambda_1, \lambda_3, \lambda_6, \lambda_7, \lambda_8\}, SC_{p_4^1} = 5 & & \\
 W_{p_5^1} &= \{\lambda_1, \lambda_2, \lambda_4, \lambda_6\}, SC_{p_5^1} = 4 & W_{p_5^2} &= \{\lambda_1, \lambda_2, \lambda_4, \lambda_6, \lambda_7\}, SC_{p_5^2} = 5
 \end{aligned}$$

By using the concept of grouping, the multicast tree is divided into five groups as

$$\begin{aligned}
 G_1 &= \{d_1^1, d_2^1, d_4^1\} \\
 G_2 &= \{d_3^1, d_5^1\} \\
 G_3 &= \{d_3^2, d_5^2\} \\
 G_4 &= \{d_1^2, d_2^2, d_4^2\} \\
 G_5 &= \{d_3^3\}
 \end{aligned}$$

The available wavelengths of each group W_{G_z} and the group capacity GC_z can be calculated in the following:

$$\begin{aligned}
 W_{G_1} &= W_{d_1^1} \cap W_{d_2^1} \cap W_{d_4^1} = \{\lambda_2, \lambda_3, \lambda_4, \lambda_6\}, GC_1 = 4 \\
 W_{G_2} &= W_{d_3^1} \cap W_{d_5^1} = \{\lambda_1, \lambda_2, \lambda_4, \lambda_6, \lambda_7\}, GC_2 = 5 \\
 W_{G_3} &= W_{d_3^2} \cap W_{d_5^2} = \{\lambda_3, \lambda_6, \lambda_8\}, GC_3 = 4 \\
 W_{G_4} &= W_{d_1^2} \cap W_{d_2^2} \cap W_{d_4^2} = \{\lambda_1, \lambda_4, \lambda_8\}, GC_4 = 3 \\
 W_{G_5} &= W_{d_3^3} = \{\lambda_1, \lambda_3, \lambda_4, \lambda_5, \lambda_7, \lambda_8\}, GC_5 = 6
 \end{aligned}$$

For the First-fit scheme, λ_1 will be assigned for W_{G_2} , W_{G_3} , W_{G_4} , and W_{G_5} and λ_2 will be assigned for W_{G_1} . And, for random selection scheme, the wavelengths will be randomly chosen from the available wavelengths of W_{G_1} , W_{G_2} , W_{G_3} , W_{G_4} , and W_{G_5} , *e.g.* we select λ_6 , λ_1 , λ_6 , λ_8 , and λ_3 for those groups, respectively. And for the proposed MEF algorithm, the decreased capacity of each wavelength in each group is shown in Table 1 and the selected wavelengths for these groups are λ_6 , λ_1 , λ_8 , λ_4 , and λ_1 , respectively. And the

Table 1. Decreased capacity for different wavelength assignment.

Group	Wavelength	Affected potential path	Decreased capacity
G_1	λ_2	p_3	1
	λ_3	p_3	1
	λ_4	p_3	1
	λ_6	–	0
G_2	$\lambda_1, \lambda_2, \lambda_4, \lambda_6, \lambda_7$	–	0
G_3	λ_1	p_2, p_5	2
	λ_3	p_2	1
	λ_6	p_5	1
	λ_8	–	0
G_4	λ_1	p_4	1
	λ_4	–	0
	λ_8	p_4	1
G_5	$\lambda_1, \lambda_3, \lambda_4, \lambda_5, \lambda_7, \lambda_8$	–	0

decreased network capacities of the proposed FF, R, and MEF approaches are 4, 2, and 0, respectively. The proposed MEF scheme has the least decreased capacity.

4. PERFORMANCE SIMULATIONS

There are two simulation environments are provided in this paper. One is the well known NFSNET topology, and the other one is generated randomly.

4.1 NFSNET Topology

In order to examine the performance of the proposed scheme, a topology with twenty four nodes and forty-three optical links [9], as shown in Fig. 5, is applied for exhaustive simulations. By varying the number of wavelength on each link of the topology and a lot of multicast trees are generated for simulations and all of the results have the similar phenomenon. The illustrated multicast trees are the two representatives. The simulation parameters are described as follows. We assume that each optical link has 16

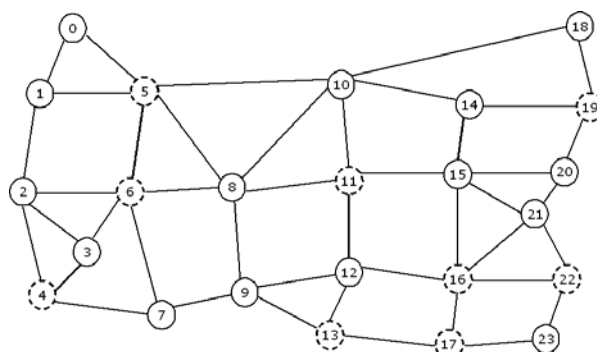


Fig. 5. Simulation topology.

wavelengths. The dot circle nodes (*i.e.* node 4, 5, 6, 11, 13, 16, 17, 19, and 22) shown in Fig. 5 are supposed to have the capability of wavelength conversion. We generate some exist traffic to emulate the current sate of topology. To fairly examine the resource utilization of each scheme, various potential paths are generated and each result point in our simulation is calculated from the average of 1000 randomly generated potential traffic cases.

Simulations for the influences of both the number of potential paths and the number of the destination nodes of the multicast tree are performed. The simulations results of the proposed scheme with First-fit, Random, and MEF approaches are compared with respect to the upper bound.

4.1.1 Influenced by the number of potential paths

Two multicast requests under the circumstance of potential paths P are performed in our simulations. Based on Fig. 5, one multicast request is assumed to be rooted by the source node 23 with 8 destination nodes, *i.e.* $\langle 23, \{2, 14, 3, 16, 19, 10, 11, 5\} \rangle$, and the other multicast request has 10 destination nodes with the source node 2, *i.e.* $\langle 2, \{18, 4, 10, 15, 23, 14, 21, 9, 5, 1\} \rangle$. The potential traffic is point to point connection and the source node and the destination node of each potential path are randomly selected from the simulation topology. The number of generated potential paths increases from 12 to 120 during this simulation. The results of decreased network capacity versus different number of potential paths for both multicast requests are depicted in Figs. 6 and 7, respectively. Fig. 6 is the case of 8 destination nodes while Fig. 7 is the case of 10 destination nodes. As the potential path is randomly selected, the generated potential paths may not overlap with the multicast request, therefore, we use p' to indicate the number of overlapped potential paths in both figures. The meaning of decreased network capacity is defined as the number of potential paths which affected by the wavelength assigned in the multicast request. In the worst case, if the wavelengths of the multicast tree are not properly assigned, all of the overlapped potential paths will be affected. Thus, the curves of p' in Figs. 6 and 7 can be regarded as the upper bound of the decreased capacity.

As shown in Figs. 6 and 7, the proposed wavelength assignment schemes can effectively reduce the decreased network capacity in SWCN environment. Our scheme can be further divided into First-fit, Random, and MEF approaches for group wavelength

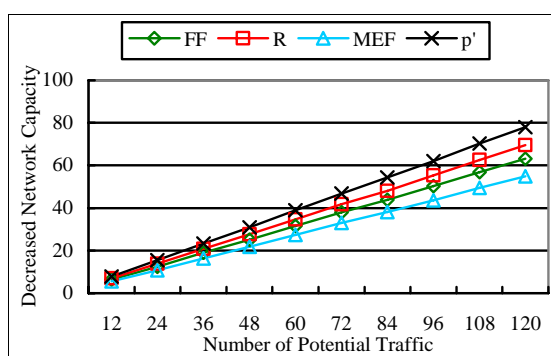


Fig. 6. Impact of network capacity vs. potential paths for multicast with 8 destinations.

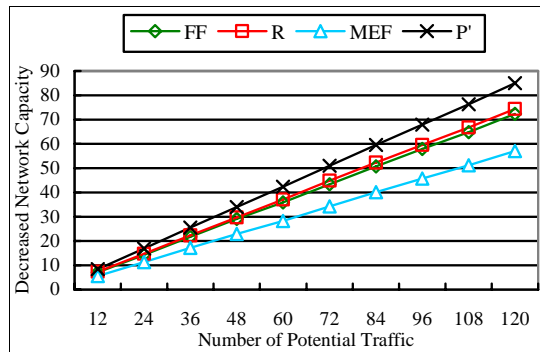


Fig. 7. Impact of network capacity vs. potential paths for multicast with 10 destinations.

assignment. And the proposed MEF approach is the best one among them. For example, in Fig. 6, the number of overlapped potential paths is about 78 (*i.e.* p') when the total number of potential paths is 120. And, among the 78 overlapped paths, the number of influenced paths is only about 52 by using MEF approach, while the First-fit and Random selection schemes are 62 and 70, respectively. Thus, the MEF scheme can save up to 33.3% bandwidth (calculated as $(78 - 52)/78 = 33.3\%$) while the other two schemes save only 20.5% and 10.25%, respectively. The main reason is that the MEF approach evaluates the minimum effect for the wavelength assignment in accordance with group concept.

4.1.2 Influenced by the number of destination nodes

As shown in Fig. 5, the simulation topology has 24 nodes and each multicast request shall have at least two destination nodes and the maximum number of destination nodes is 23 (excluding the root node). Assume that the multicast request is rooted by node 23 and is pre-constructed as shown in Fig. 8. Numbers of destinations are increased from 2 to 23 according to the randomly generated order, indicated as d_i . For example, the destination nodes are 2, 3, and 14 when the number of destinations is 3, and node 16 will

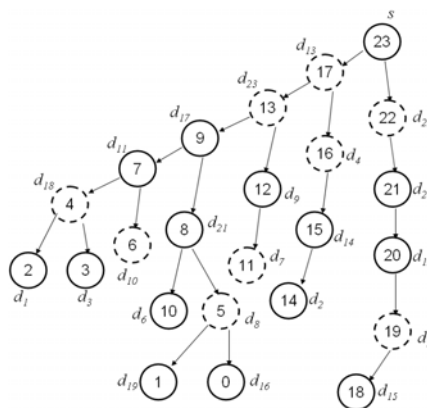


Fig. 8. Pre-constructed multicast tree rooted by node 23.

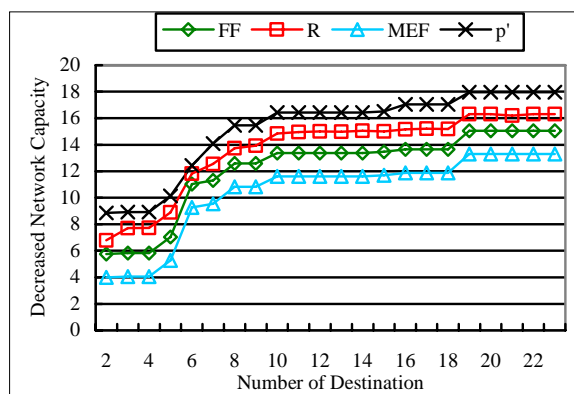


Fig. 9. Simulation results of the impact by the number of destination nodes.

be added when the number of destinations is 4 during the simulation. The number of randomly generated potential paths is fixed to be 24 in this simulation. The result of decreased capacity is shown in Fig. 9.

We can find that all of the three approaches have the capability to minimize the decreased network capacity. It indicates that the MEF approach is still the best one among them. For example that the upper bound (p') is 18 when the number of destination nodes is 20. And the number of affected paths by using MEF approach is only about 13, while the other two approaches are 15 and 16, respectively.

4.2 Random Network Topologies

The proposed algorithm can be regarded as a general method to assign wavelength for multicast in WDM network (including the WDM network without wavelength conversion node as discussed in [8]). In order to compare the proposed scheme with the scheme proposed in [8] fairly, ten kinds of network topology without wavelength conversion node were randomly generated for the simulations of the proposed MEF scheme and the SCG scheme proposed in [8]. For each generated network topology, 100 different multicast trees and potential request pairs were applied. Each simulation result was calculated from the average of 1000 simulation data points. This simulation model is similar to that performed in [8]. For the generation of a network topology, each topology is assumed to have 100 nodes and the out degree of each node is uniformly distributed in range between 1 and 10. For each optical link, there are K available wavelengths, where K is uniformly distributed in range between 3 and 16. And each link has 3 wavelengths at least. To simulate the current state of network topology, each link randomly selects K wavelengths from λ_1 to λ_{16} . In addition to examining the decreased network capacity, two performance metrics, wavelength consumed per hop and per destination for the multicast tree, have been measured. Wavelength consumed per hop is defined as the summation of wavelengths, which are used by every link, divided by the total hop count of every source destination pair in the multicast tree. The range of this value is between 0 and 1. For the worst case, *i.e.*, each hop is assigned by an individual wavelength even if the hop is shared with another source-destination pair, this value will be equal to one. Wavelength

consumed per destination is defined as the summation of wavelengths, which are used by every link, divided by the total number of destinations in the multicast tree. This value will be equal to or greater than one. The smaller this value is, the more cost-effective the utilization will be. The simulation results are shown in Table 2. It is found that MEF scheme is superior to SCG scheme in decreased network capacity and wavelength consumption.

Table 2. MEF scheme vs. SCG scheme.

	MEF	SCG
Average decreased network capacity	10.753	11.614
Wavelength consumed per hop	0.721621	0.8313015
Wavelength consumed per destination	1.987554	2.2900215
Percentages of superiority in minimizing the decreased network capacity	56%	29%

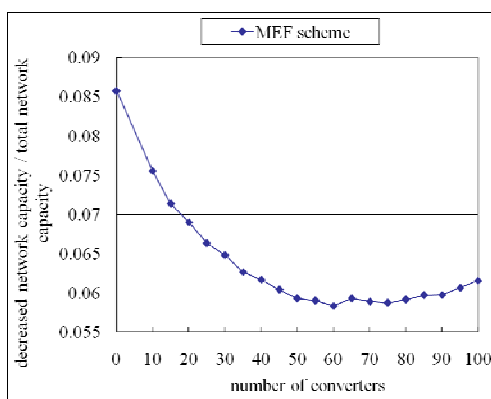


Fig. 10. Ratios of decreased network capacity over total capacity versus number of converters.

Further simulation is performed to examine the impact of the number of converters and the result is shown in Fig. 10. Generally, if the number of converters increases, the wavelength continuity constraint gets looser and the wavelength can be more effectively utilized. The ratio of decreased network capacity over total network capacity becomes small as the number of converters increases. It means that the consumed capacity is less than the increased capacity by adding converters. We found that although increasing the number of converters can improve the effective capacity, the enhancement is not significant when the number of converters is greater than 35. Thus, it is not necessary for all nodes to have the capability of wavelength conversion during the deployment. It is noted that, in Fig. 10, the ratio is slightly rising when the number of converters is greater than 60. The reason is that when the number of converters exceeds 60, more than half of the network nodes have the conversion capability. The total network capacity becomes saturation. In accordance with simulation we observed, the decreased network capacity is still increasing but the difference is less than 0.5%.

5. CONCLUSIONS

In this paper, we analyze the scheme for the assignment of wavelength in a sparse wavelength conversion WDM network. Our main contribution is to propose a generalized wavelength assignment algorithm of SWCN in a systematic manner. In addition to the systematic approach, both of multicast request and the potential paths are segmented and grouped for the effective assignment of wavelength so that the influence on network capacity can be minimized. Based on the foundation of the proposed algorithm, three different approaches for the selection of the wavelength are provided and discussed. Our simulation results show that the proposed scheme demonstrates a quite good performance in minimizing the decreased network capacity (and, hence, maximizing the network capacity). It shall also be noted that the impact of multicast routing is not considered in this paper. We believe that multicast routing in SWCN shall also play an important role for the improvement of resource utilization and it is one of the issues we are working on.

REFERENCES

1. B. Mukherjee, "WDM optical networks: Progress and challenges," *IEEE Journal on Selected Areas in Communications*, Vol. 18, 2000, pp. 1810-1824.
2. I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: A novel approach to high bandwidth optical WANs," *IEEE Transactions on Communications*, Vol. 40, 1992, pp. 1171-1182.
3. L. H. Sahasrabudde and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," *IEEE Communications Magazine*, Vol. 37, 1999, pp. 67-73.
4. S. Subramania and R. Barry, "Wavelength assignment in fixed routing WDM networks," in *Proceedings of IEEE International Conference on Communications*, Vol. 1, 1997, pp. 406-410.
5. J. Strand, R. Doverspike, and G. Li, "Importance of wavelength conversion in an optical network," *Optical Networks Magazine*, 2001, pp. 33-44.
6. S. Subramaniam, M. Azizoglu, and A. K. Somani, "All-optical networks with sparse wavelength conversion," *IEEE/ACM Transactions on Networking*, Vol. 4, 1996, pp. 544-557.
7. B. Li, X. W. Chu, and K. Sohraby, "Routing and wavelength assignment vs. wavelength converter placement in all-optical networks," *IEEE Communications Magazine*, Vol. 41, 2003, pp. S22-S28.
8. J. Wang and B. Chen, "Dynamic wavelength assignment for multicast in all-optical WDM networks to maximize the network capacity," *IEEE Journal on Selected Areas in Communications*, Vol. 21, 2003, pp. 1274-1284.
9. K. Zhu, H. Zang, and B. Mukherjee, "A comprehensive study on next-generation optical grooming switches," *IEEE Journal on Selected Areas in Communications*, Vol. 21, 2003, pp. 1173-1186.
10. Y. Zhu, G. N. Rouskas, and H. G. Perros, "A comparison of allocation policies in wavelength routing networks," *Photonic Network Communications Journal*, Vol. 2, 2000, pp. 265-293.
11. B. Chen and J. Wang, "Efficient routing and wavelength assignment for multicast in

- WDM networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 20, 2002, pp. 97-109.
12. X. Jia, D. Du, X. Hu, M. Lee, and J. Gu, “Optimization of wavelength assignment for QoS multicast in WDM networks,” *IEEE Transactions on Communications*, Vol. 49, 2001, pp. 341-350.
 13. X. Jia, X. Hu, L. Ruan, and J. Sun, “Multicast routing, load balancing, and wavelength assignment on tree of rings,” *IEEE Communication Letters*, Vol. 6, 2002, pp. 79-81.
 14. G. S. Poo and Y. Z. Zh, “A new multicast wavelength assignment algorithm in wavelength-routed WDM networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 24, 2006, pp. 2-12.
 15. Y. Zhou and G. S. Poo, “Multicast wavelength assignment for sparse wavelength conversion in WDM networks,” in *Proceedings of IEEE INFOCOM*, 2006, pp. 1-10.



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