On-Line Multicast Routing in WDM Grooming Networks

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***Abstract*— This paper considers the problem of on-line multicast routing in WDM grooming optical mesh networks without wavelength conversion capability. In such networks, provisioning of connection requests with fractional wavelength capacity requirements is achieved by dividing a wavelength into multiple time slots and multiplexing traffic on the wavelength. We present an on-line multicast traffic grooming algorithm for the concerned problem. The objective is to efficiently route multicast requests with sub-wavelength capacity requirements onto high-capacity wavelengths, and balance the load on the links in the network at the same time. To do so, we propose a cost function, which not only encourages grooming new requests onto the wavelengths that are being used by existing traffic, but also performs load balancing by intelligently increasing the cost of using wavelengths on links. The performance results obtained by experiments on a representative sized mesh network show that the proposed algorithm outperforms the other existing algorithms.**

***Index Terms*— Multicasting, optical WDM-TDM switched networks, optical time slot interchanger (OTSI), traffic grooming, load balancing**

I. Introduction

Wavelength Division Multiplexing (WDM) optical networks provide enormous bandwidth, and are promising candidates for next generation high-speed networks [1]. WDM systems facilitate concurrent transmission of information on different wavelengths within the same fiber, with capacities of wavelengths being in the order of OC-48/OC-192/OC-768 (2.48Gbps/10Gbps/40Gbps). However, as most applications require only sub-wavelength capacities, the available bandwidth on a single wavelength far exceeds the capacity requirement of a typical connection request. For example, the bandwidth required by HDTV is only about *20Mbps*.

As wavelengths are critical resources in WDM optical networks, the bandwidth available on wavelengths needs to be used efficiently. One approach to provisioning sub-wavelength capacity requests is to divide a wavelength into multiple time slots and multiplex different requests onto different time slots [2], [8]. Thus, upto p requests can share the same wavelength, assuming that each wavelength is divided into p time slots and each request occupies one time slot. The resulting multiwavelength optical time division multiplexed network is referred to as a *WDM-TDM network* or a *WDM grooming network*. The nodes in a WDM-TDM network have the functionality of multiplexing (demultiplexing) low rate traffic onto (from) a wavelength, and switching them from one lightpath to another, where a *lightpath* is an all-optical, full-wavelength-capacity transmission medium that uses the same wavelength along the links in the routing path. A connection between a source node and a destination node is setup by assigning time slots on every link in the routing path. Intermediate nodes along the path then switch time slots from one link to the next. Development in optical switching technology has paved the way for fast all-optical switches [3], [4], [5]. All-optical switching seeks to eliminate electronic switching components and has other potential benefits such as protocol transparency and bit rate independence. Use of such all-optical switches in conjunction with fiber delay lines as time slot interchangers have helped realize WDM-TDM switched networks [6], [7].

A wavelength converter is a device that allows the conversion of a signal on one wavelength on to another wavelength. In optical networks without wavelength converters, each message can only be switched from a certain wavelength at an input port to the same wavelength on an output port. Although wavelength converters improve the network blocking performance, it is well known that all-optical wavelength converters are prohibitively expensive. Due to an increasing interest in developing all-optical solutions for traffic grooming, the first generation optical switching technology is expected to obey the wavelength continuity constraint [9], i.e. a connection between two endpoints can be setup on one wavelength only, and wavelength conversion is not allowed at the intermediate nodes along the routing path. Therefore, a node in such a WDM-TDM network can switch time-slots from a certain wavelength at an input port to different time-slots on any output port. The switching, however, is subject to the wavelength continuity constraint.

As popularity of multicast services such as tele-conferencing and distance learning continue to increase, it is imperative for communication networks to support these services efficiently and in a cost-effective manner. It is expected that a large portion of traffic in high speed networks will be multicast in nature [18]. Multicasting involves the simultaneous transmission of information from a source node to multiple destinations. In WDM networks, multicast requests can be efficiently setup using the concept of *light-trees* [10]. In this approach, individual nodes are equipped with optical splitters that are capable of duplicating an incoming optical signal into two or more identical copies. Provisioning multicast requests using light-trees significantly improves the throughput and the performance of the network.

A. Related Work

As commercial networks evolve from rings to arbitrary mesh topologies, addressing the traffic grooming problem in the context of mesh networks is extremely pragmatic. Most previous research on traffic grooming has focused on unicast communication. [12] provides an overview of the architectures for unicast traffic grooming. ILP and heuristics for static unicast traffic grooming appear in [13], [14]. Dynamic unicast traffic grooming problem is addressed in [15], [16]. In [2], [9], the authors consider the general problem of dynamic routing in WDM-TDM switched networks. In [8], the authors propose a generalized network model called the Trunk Switched Network (TSN) to facilitate the modeling and analysis of WDM-TDM switched networks.

Recent work that addresses static multicast grooming appear in [17], [18], [19]. In [17], multicast grooming in WDM networks with sparse splitting capabilities is considered. An ILP formulation is provided along with heuristics to minimize the number of wavelengths. [18] presents an ILP formulation along with heuristic algorithms to minimize the network cost in terms of the electronic equipment and the maximum number of wavelengths, while [19] gives a non-linear formulation with heuristics to minimize the number of electronic ports.

On-line routing of sub-wavelength multicast requests, however, has received very little attention in the literature. In [20], the authors develop an analytical model for evaluating the blocking performance of tree establishment in WDM-TDM switched optical networks. They extend the TSN model proposed in [8] to the context of multicasting. In [21], the authors present a hypergraph logical topology design for grooming multicast demands, while in [22], a Shortest Path Tree heuristic is presented for constructing multicast trees.

B. Our Contributions

To the best of our knowledge, we are unaware of any previous work that addresses the on-line multicast traffic grooming problem in WDM-TDM switched mesh networks. In this paper, we first address

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the problem and propose a node architecture for supporting sub-wavelength demand multicast traffic grooming in such networks. We then present an on-line algorithm that integrates multicast traffic grooming and load balancing with the aim of maximizing the request acceptance of future incoming connections. We finally conduct experiments by simulation to evaluate the performance of the proposed algorithm. The experimental results show that the proposed algorithm outperforms the other existing algorithms.

The rest of the paper is organized as follows. The node architecture and the problem definition appear in Section II. The proposed heuristic algorithm is presented in Section III, and the simulation results are discussed and analyzed in Section IV. Section V concludes the paper.

II. Preliminaries

A. Node Architecture

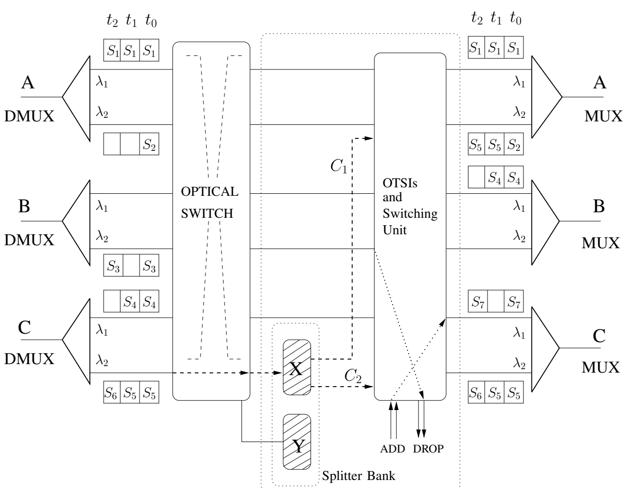

Fig. 1. Node architecture for sub-wavelength demand multicast traffic grooming with all-optical switches and OTSIs

A WDM-TDM switched network consists of switching nodes with communication fiber links interconnecting the nodes. Each fiber link carries a certain number of wavelengths and each wavelength is further divided into a number of time slots. The node architecture for sub-wavelength demand multicast grooming in such a WDM-TDM switched network is shown in Fig. 1. The figure represents a node supporting three links (A, B, C), two wavelengths per link (λ_1, λ_2) and three time slots per wavelength (t_0, t_1, t_2). S_4 and S_6 are unicast sessions utilizing 2 and 1 time slot of bandwidth, while S_1, S_2, S_3, S_5, and S_7 are multicast sessions utilizing 3, 1, 2, 2 and 2 time slots of bandwidth respectively.

S_4 is switched on λ_1 from input fiber link C to output fiber link B. As branching does not occur at the node for multicast sessions S_1 and S_2 (i.e. S_1 and S_2 need not be split at the node), they are switched on λ_1 and λ_2 from input link A to the same output link. Session S_3 arriving on λ_2 from input fiber link B is dropped locally at the node while Session S_7 is added at the node and switched to output link C on λ_1. To support multicasting in *all-optical networks*, optical splitters are needed to replicate an incoming optical signal into two or more identical outgoing signals. In the figure, the splitter bank consisting of optical splitters **X** and **Y** perform optical multicasting. Since there are three time slots per wavelength, the optical switch can be set in only three possible settings at any given time. When the switch is set to time slots t_0 and t_1, incoming multicast signal S_5 is split into *two identical copies* C_1 and C_2 by the optical splitter **X**. Signals can be delayed using Optical Time Slot Interchangers (OTSIs), therefore, time slots on an incoming signal can be mapped on to different time slots on the outgoing signal. In the figure, the OTSI introduces a delay of one time slot duration so that t_0 and t_1 on one copy of the signal S_5 (C_1 on λ_2) is mapped on to t_1 and t_2 at the output link A respectively. When the switch is set to time slot t_2, S_6 is switched on λ_2 to the same time slot on output link C.

B. Problem Definition

The physical topology of a WDM-TDM switched mesh network is represented by a graph $G = (V, E)$, consisting of $|V| = n$ nodes and $|E| = m$ links interconnecting the nodes. Each link in the physical topology is bidirectional and is modeled as a pair of unidirectional links. $W = \{\lambda_1, \lambda_2, \ldots\ldots, \lambda_w\}$ is the set of available wavelengths in the network. A multicast request i is represented by a quadruple $(s_i, D_i, \beta_i, \Delta_i)$, where $s_i \in V$ is the source, $D_i \subseteq V$ is the destination set, β_i is the required bandwidth and Δ_i is the duration of the multicast request.

Given the current network state (routes and wavelengths being used by existing traffic), the problem is to construct a minimum cost bandwidth guaranteed tree T_i^{λ} on a wavelength $\lambda \in W$ that connects s_i to all the destination nodes in D_i. The aim is to maximize the multicast request acceptance ratio, i.e. the throughput of the network. We assume that the established requests cannot be interrupted and the sequence of incoming multicast requests is not known in advance. We refer to this problem as the *Multicast Routing and Wavelength Assignment (MCRWA)* problem.

C. Tree construction algorithms

To solve MCRWA, a common approach is to construct a multicast tree connecting the source node to all the destinations in the multicast group. This is the well-known *Steiner Tree Problem* known to be NP-Complete [23]. Various heuristics and approximation algorithms based on the Minimum Spanning Tree (MST) and the Shortest Path Tree (SPT) have been proposed for it.

Generally speaking, routing algorithms can be classified as being either static or dynamic [24]. In the static scheme, routes are computed without considering the current network state. The possible routes between source destination pairs are computed a priori, usually based on the shortest path criterion. The dynamic scheme makes use of the current utilization of links and the state of the network in choosing a route. In general, *Fixed SPT* and *Adaptive SPT* multicast routing algorithms are used to route multicast traffic [24], [22].

(i) Fixed Shortest Path Tree (FSPT). A single shortest path based on the hop count is computed between each source destination pair without considering the state of the network. The union of shortest paths from the source node to all the destinations in the multicast group generates the tree.

(ii) Fixed-Alternate Shortest Path Tree (FASPT). This scheme is similar to FSPT, but offers greater flexibility in selecting routes, as a *set of routes* are assigned to each source destination pair. All shortest paths based on the hop count between source destination pairs are candidate routes for constructing the tree.

(iii) Adaptive Shortest Path Tree (ASPT). The FSPT and FASPT are examples of static routing algorithms whereas ASPT is a dynamic routing algorithm. Here, the routes are computed taking into account the current network state. Only wavelength-links with sufficient bandwidth to accommodate the multicast request are considered for route computation. The path that minimizes the total number of hops between the source node and each destination of the multicast group is then determined. If two paths have the same hop count, then the tie is broken by using the first-fit wavelength assignment policy. The union of these individual shortest paths generates the resultant multicast tree. To illustrate how heuristic ASPT works, we consider the example shown in Fig. 2, that represents a five node subnet - 0, 1, 2, 3, 4, of a large wide area mesh network. Assume the current network configuration of this subnet to be as follows. One wavelength λ_0 available on links $0-1$ and $1-2$, and two wavelengths λ_0, λ_1 available on links $0-4$, $4-3$ and $3-2$ respectively. We further assume that the total capacity available on a wavelength is 1. The order of multicast sessions arriving are: M_1: $0 \rightarrow \{1, 2\}$, M_2: $0 \rightarrow \{2, 3\}$ and M_3:

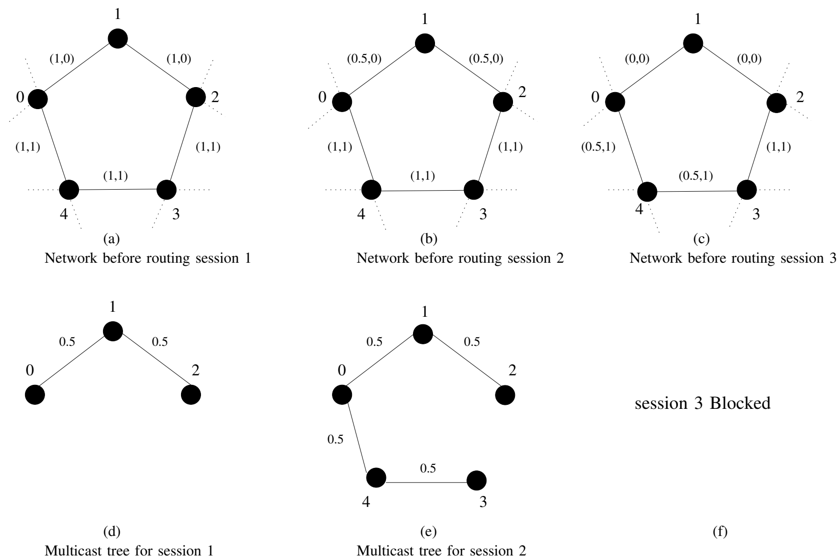

Fig. 2. Example illustrating the Adaptive SPT routing scheme

$1 \rightarrow \{2, 3\}$. Each session requests bandwidth equivalent to half of the wavelength capacity. The value within the parenthesis along the links in the figure indicate the amount of free bandwidth available on λ_0 and λ_1 respectively.

M_1 is routed as shown in Fig. 2(d) on λ_0. There are many instances where a destination node in a multicast group may want to transmit information to all the other destinations in the group as well as to the source node. For example, a student participating in a distance learning program may want to ask questions to the instructor and to other fellow students. To facilitate this, the bandwidth requested by a session is reserved along the links in either direction. Thus, following the establishment of M_1, M_2 is routed as shown in Fig. 2(e), also on λ_0. As a result, node 1 gets *logically disconnected* from the network along with the links $0-1$ and $1-2$, since no further wavelengths are available on these links while M_1 and M_2 are active. By logical disconnection we mean, the links incident to a node *cannot* be used by future connection requests as they do not have any more wavelengths available. In provisioning high speed connections, traffic requests are expected to have long holding times [11]. Thus, logical disconnection of nodes result in fewer routing paths for each subsequent connection request, increasing the number of blocked requests and in turn leading to significant loss of revenue. Consequently, the new session M_3 is blocked due to the lack of available wavelengths to route it.

III. On-Line Multicast Traffic Grooming Algorithm

A. Overview of the proposed algorithm

We propose a multicast routing scheme, On-Line Multicast Traffic Grooming Algorithm (OMTGA), which (i) encourages grooming new sub-wavelength multicast requests onto the wavelengths that are being used by existing multicast traffic, and (ii) incorporates load balancing functionality simultaneously. To do so, we introduce a cost function that takes into consideration the *total load on a link* and the *residual available bandwidth on each wavelength*. For every new incoming multicast request, the Shortest Path Tree heuristic is used to construct the multicast tree. Since wavelength conversion is not allowed, each multicast request can be routed on one wavelength only. Thus, at most w multicast trees can be generated, where w is the total number of wavelengths available in the network. Out of all the resulting wavelengths that can be used to carry the multicast traffic, the wavelength corresponding to the least cost tree is then selected. Here, the cost of a multicast tree is the sum of the cost of all the links in the tree. If two trees have the same cost, then the first-fit wavelength assignment policy is employed to break the tie. The bandwidth requested by the multicast session is then reserved along the links in the tree. In the following, we use an example (see Fig. 3) to explain the idea behind the proposed algorithm.

As in the ASPT scheme, M_1 is routed as shown in Fig. 3(d) on λ_0. This increases the load on the links $0-1$ and $1-2$. Since links $0-4$, $4-3$, and $3-2$ have more wavelengths, it is desirable to use these links to route future requests and prevent the depletion of wavelengths on links $0-1$ and $1-2$. Therefore, higher costs are assigned to λ_0 on links $0-1$ and $1-2$ for subsequent incoming requests. As a result, M_2 is routed on λ_0 on the shortest path tree as shown in Fig. 3(e). Now M_3 can be successfully established on λ_0 as shown in Fig. 3(f). Therefore, unlike in the Adaptive SPT routing strategy, M_3 is not blocked in the proposed routing scheme.

B. Cost Function

We denote Ω as the total available bandwidth per wavelength. Let $\mu_{u,v}$ represent the total available bandwidth on a link between nodes u and v. Therefore, we have

$$\forall (u,v) \in E: \qquad \mu_{u,v} = w \times \Omega. \tag{1}$$

For convenience, we normalize the requested bandwidth to the total available bandwidth on a link. Therefore,

$$\hat{\beta}_i(u,v) = \frac{\beta_i}{\mu_{u,v}}. \tag{2}$$

Let $\mathcal{T} = \{T_1, T_2, T_3, \cdots\cdots\cdots, T_k\}$ be the set of multicast trees assigned to requests 1 through k. If a multicast request j is rejected, or terminates before the arrival of a new multicast request, then $T_j = \emptyset$, where T_j is the multicast tree for request j $(1 \leq j \leq k)$. Therefore, the load on link $(u,v) \in E$ after considering request k is defined as

$$l^k_{u,v} = \sum_{\substack{j=1 \\ (u,v) \in T_j}}^{k} \hat{\beta}_j(u,v). \tag{3}$$

In WDM-TDM switched networks, bandwidth requirements of requests are expressed in terms of the number of time slots. In this work, we assume that each wavelength is sub-divided into 16 time slots and the capacity of each time slot is equivalent to 1 OC-3 channel. Therefore, the total capacity of each wavelength is equivalent to 1 OC-48 channel, and we have $\Omega = 16$ OC-3s.

Let $\tau_{j,\lambda'}(u,v)$ be the number of OC-3 channels being used on link (u,v) by request j on wavelength $\lambda' \in W$. Then, after considering multicast request k, the total number of λ' OC-3 channels being used on link (u,v) is

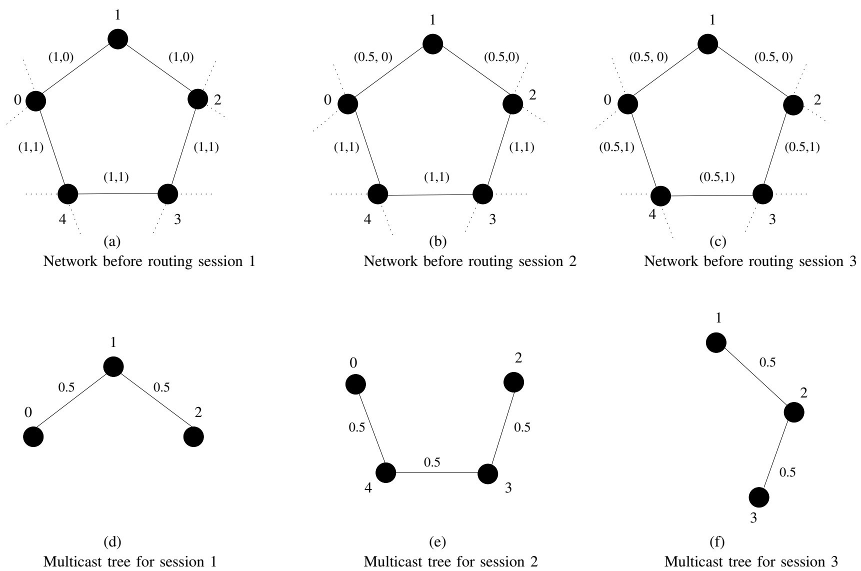

Fig. 3. Multicast traffic grooming using the OMTGA routing scheme

$$U^{k,\lambda'}_{u,v} = \sum_{\substack{j=1 \\ (u,v) \in T_j}}^{k} \tau_{j,\lambda'}(u,v). \quad (4)$$

When a new multicast request i arrives, we assign costs to each wavelength $\lambda' \in W$ on the links in E as follows.

(i) If the capacity of λ' available on link (u,v) is equal to Ω, i.e. λ' is not being used by any existing multicast request, then the cost of using λ' on it is

$$\Psi^{\lambda'}_{u,v} = a^{l^k_{u,v}} \left(a^{\hat{\beta}_i(u,v)} - 1 \right). \quad (5)$$

(ii) Otherwise, λ' is currently being used by existing multicast requests, and two cases arise.

Case 1. If the residual capacity of λ' on link (u,v) is less than Ω, but is no less than the requested bandwidth β_i, then the cost of using λ' on it is

$$\Psi^{\lambda'}_{u,v} = \frac{a^{l^k_{u,v}} \left(a^{\hat{\beta}_i(u,v)} - 1 \right)}{{R_{\lambda'}(u,v)}^{b}}, \quad (6)$$

where a and b are appropriately chosen constants. Here, $R_{\lambda'}(u,v)$ is the residual capacity of λ' on link (u,v) after considering the first k requests, and is given by

$$R_{\lambda'}(u,v) = 1 - \frac{U^{k,\lambda'}_{u,v}}{\Omega}. \quad (7)$$

It is important to observe that, to realize load balancing and grooming interests, the constants a and b in the cost function must be greater than 1.

Case 2. If the residual capacity of λ' on link (u,v) is less than β_i, then $\Psi^{\lambda'}_{u,v} = \infty$, which means it cannot be used to construct the multicast tree.

Note that, from Equation (5), if λ' is not being used by any existing multicast request on link (u,v) (i.e. full wavelength capacity of λ' is available on link (u,v)), then the cost assigned to it represents the change in its relative load that would occur if it were to be used by the new multicast request [25]. From Equation (6), if the residual capacity of λ' on link (u,v) is less than Ω, but is no less than the requested bandwidth β_i, then the cost of λ' on this link is expressed as a function of the change in its relative load and the residual capacity of λ'. In other words, load balancing is realized by increasing the cost of using wavelengths on heavily loaded links, thus discouraging them from being used by new multicast requests. To encourage grooming new requests onto the *wavelengths that are already being used* by existing traffic, the costs of these wavelengths are *further decreased* by a factor of their residual capacities. Therefore, among the wavelengths that are currently being used on a link, we encourage grooming on the wavelength that has the highest residual capacity. This minimizes the logical disconnection of nodes from the network and achieves our objective.

C. Algorithm

Having defined the cost function, we are ready to introduce the detailed algorithm as follows. Once a new multicast request arrives, the algorithm is executed to determine whether the request is accepted.

Algorithm OMTGA(s_i, D_i, β_i)
begin
$\mathbb{C}_{\text{MAX}} \leftarrow \infty; \lambda \leftarrow nil; T^{\lambda}_i \leftarrow nil;$
/* $\mathbb{C}_{\text{MAX}}$ is the total cost to establish request i, λ is the resulting */
/* wavelength on which to route request i, T^{λ}_i is the multicast tree*/
/* for request i, Ω is the total capacity per wavelength */
Step 1. Tear down and free the wavelength resources used by all the multicast requests that terminate before the arrival of request i.
$\forall (u,v) \in E: \hat{\beta}_i(u,v) \leftarrow \frac{\beta_i}{\mu_{u,v}}$
Step 2. **for** each wavelength $\lambda' \in W$ **do**
Step 3. Compute $RC(u,v,\lambda')$, the residual capacity of λ' on link $(u,v) \in E$
Step 4. **if** $RC(u,v,\lambda') = \Omega$ **then** $\Psi^{\lambda'}_{u,v} \leftarrow$ cost from Equation (5)
else if $\beta_i \leq RC(u,v,\lambda') < \Omega$
then $\Psi^{\lambda'}_{u,v} \leftarrow$ cost from Equation (6)
else $\Psi^{\lambda'}_{u,v} \leftarrow \infty$
endif;
endif;
Step 5. Find the shortest path from s_i to each destination in D_i w.r.t costs $\Psi^{\lambda'}_{u,v}$ using Dijkstra's algorithm. The union of individual paths from the source to each destination constitutes the multicast tree $T_{(\lambda',i)}$.
Step 6. Let c_i be the total cost of constructing the tree $T_{(\lambda',i)}$. If a path does not exist between the source to every destination node in D_i, then $c_i \leftarrow \infty$; otherwise c_i is the sum of the cost of all the links in $T_{(\lambda',i)}$.

Step 7. **if** $c_i < \mathbb{C}_{\text{MAX}}$ **then**
$\mathbb{C}_{\text{MAX}} \leftarrow c_i;\ \lambda \leftarrow \lambda';\ T_i^{\lambda} \leftarrow T_{(\lambda',i)}$
endif;
endfor;
Step 8. **if** $\mathbb{C}_{\text{MAX}} \neq \infty$ **then**
for each link $(u,v) \in T_i^{\lambda}$ **do**
$RC\,(u,v,\lambda) \leftarrow RC\,(u,v,\lambda) - \beta_i$
$RC\,(v,u,\lambda) \leftarrow RC\,(v,u,\lambda) - \beta_i$
endfor;
return multicast tree T_i^{λ}
endif;
Step 9. **return "request blocked"**
end.

We now analyze the computational complexity of the proposed algorithm. The single-source shortest path tree rooted at the source can be found using Dijkstra's algorithm, which can be implemented in $O\,(m + n \log n)$ time using Fibonacci heaps. Therefore, the time complexity of the algorithm is $O\,(w\,(m + n \log n))$ as it is run once for each $\lambda' \in W$.

IV. Simulation Results

A. Simulation Environment

To evaluate the performance of the proposed algorithm, we conducted experiments on a representative sized mesh network shown in Fig. 4, which models a typical continental backbone network and has 24 nodes and 43 fiber links. Each fiber link carries 16 wavelengths. All the nodes in the network have the architecture shown in Fig. 1. We further assume that the wavelength continuity constraint is imposed.

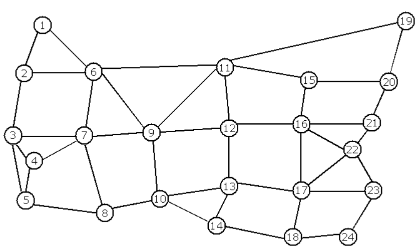

Fig. 4. A 24 node telecom network

The bandwidth required by multicast requests is uniformly distributed between 1 OC-3 and 16 OC-3s. The request arrival is a Poisson process and its duration is exponentially distributed. Each node in the network is given equal probability of being the source node. The size of each multicast group is a random number uniformly distributed between 2 and 22. The nodes in the destination set are also uniformly distributed across the network. The load (in Erlangs) on the network is increased by increasing the average connection holding time. We simulate 100,000 requests to obtain the network performance under a certain network load. The simulations were performed on a Linux PC with a 2.8 GHz Pentium IV processor and 512 MB of memory.

To identify the (a, b) value pair that gives good network performance consistently across all the network loads, we conducted experiments by iteratively varying a and b in the cost function and recording the improvement that OMTGA offered relative to ASPT. The improvement is measured in terms of the total number of multicast requests established by OMTGA and ASPT. a varies from 4 to 15 and b varies from 2 to 14. The experiment is repeated at four different network loads - 200, 350, 500 and 650 Erlangs. Fig. 5 shows the percentage improvement offered by OMTGA when a varies from 13 to 15 and b varies from 8 to 14 respectively. The improvement seen by other combination of values is lower than that shown in Fig. 5, omitted for brevity. It can be seen from the figure that a few (a, b) pairs give consistently good performance at different network loads. $(13, 12)$, $(14, 13)$ and $(15, 12)$ are a few sample values. In all our experiments, we fix the constants a and b at 15 and 12 respectively. These values are not altered as the network load varies.

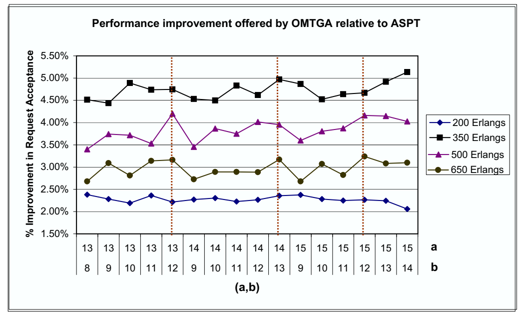

Fig. 5. Percentage improvement offered by OMTGA for different (a, b) pairs

B. Experimental Results

We compared the performance of OMTGA with the other existing algorithms - FSPT, FASPT and ASPT. The metrics used to measure the performance of the algorithms are: (i) multicast request acceptance ratio, and (ii) average resource utilization efficiency,

(i) Multicast request acceptance ratio. The request acceptance ratio curves of different routing algorithms are shown in Fig. 6. It can be observed from the figure that, when the network load (in Erlangs) is small, the percentage of requests accepted by OMTGA and ASPT is similar. This is because, at low loads the average connection holding time is less. The costs assigned to all the links derived from the cost function are nearly identical. Therefore, the behavior of OMTGA, and hence the percentage of requests accepted by it is similar to ASPT.

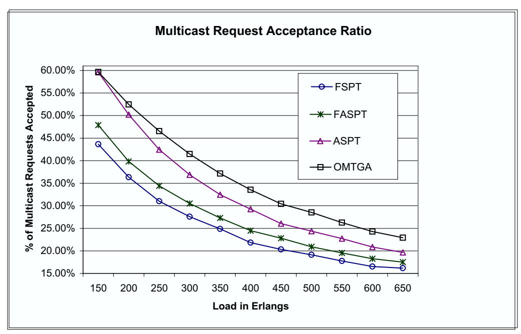

Fig. 6. Percentage of requests accepted by different routing algorithms

With the increase in the average connection holding time, the network load also increases. The exponential nature of the cost functions in Equations (5) and (6) prevent the depletion of wavelengths on heavily loaded links by assigning to it, costs, that are significantly higher than the costs assigned to lightly loaded links. This in turn leads to creation of routing paths that are distributed among the links evenly. From the figure it can be seen that, as the network load increases, the percentage of multicast requests that are accepted decreases. However, the percentage of requests accepted by OMTGA is higher than the percentage of requests accepted by the ASPT heuristic, thereby offering better performance.

To study the performance gain of the tree construction algorithms, we assume that the normal case of serving multicast requests is by using the ASPT heuristic. Therefore, the performance gain of an algorithm (say OMTGA) relative to ASPT can be calculated as follows. Let ME_{ASPT} and ME_{OMTGA} be the total number of multicast requests established by the ASPT and OMTGA routing schemes respectively. Then, the performance gain of OMTGA, U_{OMTGA}, can be defined as

$$U_{OMTGA} = \frac{ME_{OMTGA} - ME_{ASPT}}{ME_{ASPT}} \times 100 \qquad (8)$$

The performance gain of FSPT and FASPT are defined similarly.

Fig. 7 shows that the gain is negative if FSPT and FASPT are used, suggesting the inefficiency of these two schemes relative to ASPT. Recall that the network load is increased with the increase in the

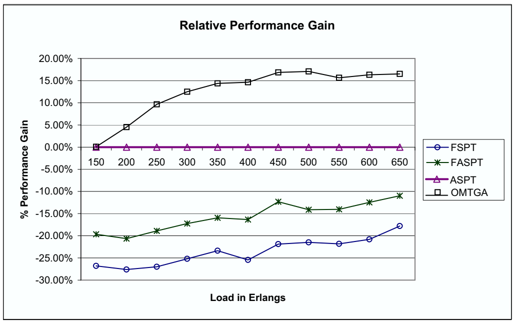

Fig. 7. Performance gain relative to ASPT

average connection holding time. Consequently, since the behavior of OMTGA and ASPT are similar at lower loads, we observe that, the performance gain obtained by OMTGA is relatively small (about 5%). However, as the network load is increased, the load balancing nature of the cost function with grooming interest efficiently routes multicast traffic and achieves high performance gains of about 15% - 18%.

(ii) Average Resource Utilization Efficiency (RUE). To understand how the allocated wavelength channels are utilized, we use the resource utilization efficiency metric. RUE represents how efficiently multicast traffic is routed and groomed. At any instant of time, RUE is determined as the ratio of the total network carried traffic (in OC-3 units) to the total network capacity allocated (total number of wavelength-links allocated times 48).

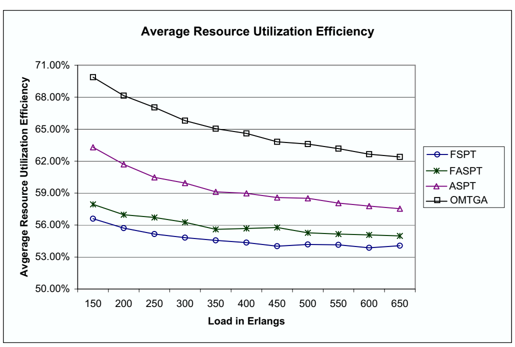

Fig. 8. Average Resource Utilization Efficiency (RUE) of different algorithms

The RUE is determined after every 25 request arrivals and is averaged over $100,000$ multicast requests. Fig. 8 shows the resulting average resource utilization efficiency (RUE) curves as the network load is varied. The higher the RUE of an algorithm, the better is the efficiency with which the algorithm routes and grooms multicast traffic. From the figure it can be observed that OMTGA has the highest RUE, followed by ASPT, FASPT and FSPT. The algorithm not only performs load balancing, but also efficiently packs new sub-wavelength multicast requests onto the wavelengths that are already being used by existing traffic. This explains why OMTGA achieves high request acceptance ratios as shown in Fig. 6.

V. Conclusion

In this paper, we investigated the on-line provisioning of sub-wavelength multicast demands in a WDM-TDM switched mesh network without wavelength conversion capability. Using a novel exponential cost function, we introduced the OMTGA algorithm for efficient multicast traffic grooming. We compared and analyzed the performance of the proposed algorithm with the other well-known heuristics - FSPT, FASPT and ASPT. Our experimental results showed that OMTGA outperforms the existing algorithms in terms of request acceptance ratio, performance gain and average resource utilization efficiency.

VI. Acknowledgment

It is acknowledged that the work by the authors was supported by research grant #DP0449431, funded by the Australian Research Council under its Discovery Schemes.

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