

# Dynamic Traffic Grooming using Fixed-Alternate Routing in WDM Mesh Optical Networks

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## Abstract

*There is a mismatch between lightpath channel capacity and traffic request capacity in wavelength division multiplexed (WDM) optical mesh networks. Traffic grooming is needed to resolve this mismatch in an efficient way. We study the dynamic traffic grooming problem in WDM mesh networks using the fixed-alternate routing (FAR) approach. Based on the FAR approach, we propose the fixed-order grooming (FOG) algorithm to support on-line provisioning of multi-granularity sub-wavelength connections. As traffic grooming involves two-layered routing, it is significantly different from the routing and wavelength assignment (RWA) problem in wavelength-routed WDM networks. We introduce the route selection problem (also called grooming node selection problem) and propose three grooming policies to address this problem. The three grooming policies are load sharing (LS), sequential grooming (SG) and minimum gap (MG). To address the wavelength and transceiver constraints, we propose another three grooming policies including least physical hop first (LPH), least virtual hop first (LVH) and least stringent resource first (LSR). Simulations are conducted to evaluate the performance of the FOG grooming algorithm and the grooming policies.*

## 1. Introduction

The emergence of wavelength division multiplexing (WDM) technology greatly increases the transmission capacity of an optical fiber by allowing simultaneous transmission of traffic on different wavelengths along a fiber. While the transmission capacity of a single wavelength has reached 10Gbps (OC-192) or even higher, the capacity requirement of a traffic request may be far less than that, possibly as low as 155Mbps (OC-3) or 622Mbps (OC-12). Thus an essential functionality of WDM networks, referred to as traffic grooming, is to

aggregate low speed traffic connections onto high speed wavelength channels in a resource-efficient way, that is, to maximize the network throughput when the resources are given or to minimize the resource consumption when the traffic requests to be satisfied are given.

Most previous work in traffic grooming concentrated on the SONET/WDM ring network architecture, partly because it is probably the only widely deployed optical network architecture [1]-[4]. With the rapid growth of Internet, WDM optical networks appear to be a cost-effective solution to meet the huge traffic demands in the core network. Several architectural options have been proposed for incorporating WDM technology into the Internet, such as IP over ATM over WDM, IP over SONET over WDM and IP over WDM [5]. Whatever the final architecture, the combination of IP and WDM is deemed an inevitable trend. Since the Internet has a complex mesh topology, traffic grooming in WDM mesh networks evoked great interest recently. A key component that enables traffic grooming in mesh networks is an Optical Cross-Connect (OXC), which is capable of multiplexing and demultiplexing traffic streams and switching traffic streams or wavelengths from an input port to an output port.

Depending on the switching granularity and the wavelength conversion capability, two types of OXCs are available: Wavelength-Grooming Cross-Connect (WGXC) and Wavelength-Selective Cross-Connect (WSXC) [6]. A WGXC is able to switch at traffic stream granularity and has full wavelength conversion capability. The switching can be either in electronic domain or optical domain, depending on the implementation of the WGXC. For networks with WGXCs, the wavelength continuity constraint for lightpaths can be relaxed. WSXCs, on the other hand, can only switch at wavelength granularity and do not have wavelength conversion capability. Thus, for a node with WSXC, grooming is carried out in the SONET Add/Drop Multiplexer (SADM) or the IP/MPLS router connected to the WSXC at that node. Fig. 1 shows a network node

equipped with a WSXC and an IP/MPLS router. A network with only WSXCs is called a constrained grooming network. We assume a constrained grooming network in this paper.

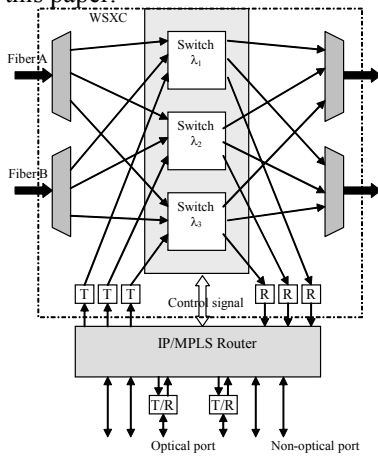


Fig. 1. A network node architecture with a WSXC and an IP router.

The dynamic traffic-grooming problem in wavelength-routed networks is generally a two-layered routing problem with traffic connections routed over lightpaths in the virtual topology layer and lightpaths routed over physical links in the physical topology layer. In a wavelength-routed network (WRN), the physical topology is a set of OXC nodes connected by fiber links. A wavelength path is referred to as a lightpath, and may span several fiber links in the physical topology. A lightpath uses a wavelength on each fiber link along its path. All the lightpaths together form the virtual topology. The multi-granularity subwavelength connections are carried over the virtual topology. A connection may traverse several lightpaths along its path and uses a portion of the bandwidth of each lightpath it traverses. Fig. 2 illustrates two lightpaths and a connection in a SONET-over-WDM optical network. Note that a lightpath uses a transmitter at the source node and uses a receiver at the destination node. Also, a connection must originate and end in the electronic domain, which is a digital cross-connect (DXC) in this case. In IP-over-WDM networks, the DXCs in Fig. 2 are replaced with IP/MPLS routers.

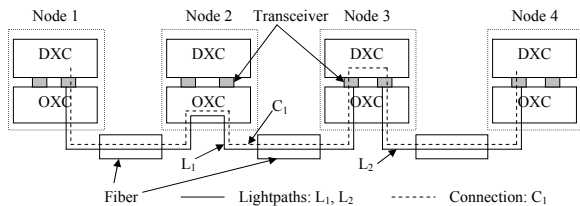


Fig. 2. Illustration of lightpaths and a connection in traffic grooming. Lightpath  $L_1$  traverses fiber link (1,2) and (2,3), lightpath  $L_2$  traverses fiber link (3,4), and connection  $C_1$  uses a two-hop path using lightpaths  $L_1$  and  $L_2$ .

## 1.1. Related Work

In [7], an ILP formulation of static traffic grooming in optical mesh networks was presented. Heuristics aimed at maximizing single-hop traffic and physical link utilization were simulated and compared. Since Internet traffic is inherently dynamic, studies in [8] and [9] explored on-line provisioning of dynamically arriving traffic requests. In [8], two routing algorithms were proposed: two-layered route-computation algorithm (TLRC), in which the route is computed independently in the physical topology layer and the virtual topology layer, and single-layered route-computation algorithm (SLRC), in which the route is computed in a single layer by integrating the physical topology and the virtual topology. Both algorithms use an adaptive routing approach [10]-[14] which calculates available routes from the current network state information each time a request arrives. Though an adaptive approach yields good performance in terms of blocking probability, it may be time-consuming for online provisioning in a large network. In [9], an integrated approach using Collaboration Group (CG) as intermediate nodes to establish a two-hop lightpath route for traffic requests was proposed. Because only routes with at most two hops are searched and the intermediate node within a two-hop route must be in the CG, the approach may not fully exploit the network capacity.

Fixed-alternate routing (FAR) [10][13][15] has been studied extensively in WDM mesh optical networks at the wavelength level. FAR predetermines a number of paths for each pair of nodes and selects one of these paths according to the network state information at run time. However, applying FAR to grooming networks is significant different. Not only does a connection is at the sub-wavelength level, but a connection can be carried in different ways even on a single path because of its two-layered routing characteristic. For example, Fig. 3 shows a candidate path and four different ways to carry a connection on this candidate path. (See section 1.2 for terminology).

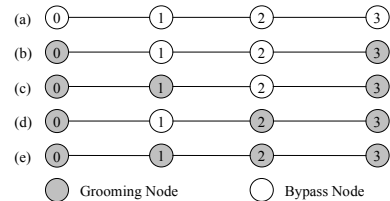


Fig. 3. Illustration of a candidate path and four different ways to carry a connection from node 0 to node 3. (a) The candidate path, (b) A single-hop (direct) route, (c) A two-hop route with lightpaths 0-1 and 1-2-3, (d) A two-hop route with lightpaths 0-1-2 and 2-3, (e) A three-hop route with lightpaths 0-1, 1-2 and 2-3.

Traffic grooming can be classified as single-hop traffic grooming and multi-hop traffic grooming. Single-hop traffic grooming only allows a connection to use a single

lightpath (a direct route). Therefore, a lightpath can only be used by connections belonging to the same source and destination pair. Multi-hop traffic grooming, on the other hand, allows a connection to use multiple lightpaths (multi-hop route). Therefore, the bandwidth of a lightpath can be shared by connections from different source and destination pairs. The work in [16][17][18] present analytical models to evaluate the blocking performance of single-hop traffic grooming. The work in [19] presents an analytical model to evaluate the blocking performance of multi-hop traffic grooming using a load sharing [20] route selection approach. All the previous work in [16][17][18][19] use fixed routing [10][13].

## 1.2. Terminology and Route Selection Problem

A grooming node is an end-node for a lightpath where the lightpath is either originating from or destined to (see Fig. 3 for an example). A bypass node is an intermediate node for a lightpath where the lightpath is bypassed in the optical domain without entering the electronic domain. Note that being a grooming (or bypass) node is only meaningful for a specific lightpath, because a grooming node for one lightpath can be a bypass node for another lightpath and vice versa. In this paper, we call a candidate path with specified grooming nodes as a connection route (or route). Hereafter, a hop in a path refers to a physical hop (fiber link), while a hop in a route refers to a virtual hop (lightpath). A single-hop route is a path with only the first node and last node being specified as the grooming nodes. Therefore, only one lightpath exists on this path. Specially, a single-hop route is also called a direct route. A two-hop route is a path with an additional grooming node besides the first and the last node. Generally, for an  $H$ -hop route, there are  $H-1$  grooming nodes besides the first node and the last node. An  $H$ -hop path can generate  $C_0^{H-1} + C_1^{H-1} + \dots + C_{H-1}^{H-1} = 2^{H-1}$  different candidate routes. The route selection problem is to select a route to carry a connection from all candidate routes on alternate paths. It can be also called grooming node selection problem because once the grooming nodes is decided on a path, the route is also decided.

## 1.3. Our Work

In this paper, we study dynamic traffic grooming in the WDM mesh optical networks using the fixed alternate routing approach. We propose the fixed-order grooming (FOG) algorithm for on-line provisioning of multi-granularity sub-wavelength connections. As the FOG algorithm can be used for both single-hop traffic grooming and multi-hop traffic grooming, we compare their performance in terms of blocking probability using simulation. To address the route selection problem in

multi-hop traffic grooming, we present three grooming policies, load sharing (LS), sequential grooming (SG) and minimum gap (MG). Wavelength and transceiver resources are two major costly components in an optical network and hence are two major constraints also. We present two grooming policies, least physical hop path first (LPH) and least virtual hop path first (LVH) to address the two resource constraints respectively. We also propose the least stringent resource first (LSR) grooming policy which considers the real time utilization of wavelengths and transceivers and has the advantages of both LPH and LVH. We further evaluate the effect of the number of alternate paths on the blocking performance.

The rest of this paper is organized as follows: Section 2 provides a definition of the dynamic traffic grooming problem studied in this paper. Section 3 presents the FOG grooming algorithm and the grooming policies including LS, SG, MG, LPH, LVH and LSR. Section 4 discusses the numerical results. Section 5 concludes the paper.

## 2. Problem Definition

The dynamic traffic grooming problem studied in this paper can be stated as follows:

### • Input

- 1). Physical topology represented as a directed graph  $G_p = (V_p, E_p)$ . The number of nodes is  $N = |V_p|$ .
- 2). The set of wavelengths supported by each fiber is  $W$  and the capacity of each wavelength is  $C$ . We assume that the same set of wavelengths is deployed on every link. The capacity of a wavelength is normalized to an integer  $C$  based on the smallest grooming granularity in the network. For example, if one wavelength supports an  $OC-192$  channel, and the smallest grooming granularity is  $OC-3$ , then  $C$  equals  $192/3 = 64$ .
- 3). The number of transmitters and receivers at each node. In this study, we assume the transceivers are tunable to any wavelength operating on the fiber.
- 4). Dynamic traffic demand ( $\Psi$ ) represented as a sequence of connection requests  $\varphi(s, d, t, \Delta t, x)$ , where  $s$  is the source node,  $d$  is the destination node,  $t$  is the arrival time of the connection request,  $\Delta t$  is the required service time for this connection and  $x$  is the required bandwidth. Suppose  $X$  is the set of connection rates supported in the network, then  $x \in X$ .

### • Constraints

- 1). Topology Constraint: The routing of connections is essentially constrained by the virtual topology, which in turn is restricted by the physical topology.
- 2). Resource Constraint: The network throughput is largely dependent on the amount of resources

deployed in the network. Besides, the distribution of resources within the network also influences the network throughput. Two kinds of resources are often considered in grooming literature: wavelengths and transceivers. To establish a lightpath on a path, there must have free wavelengths in each link along the path. In addition, there must have free transmitters at the source node and free receivers at the destination node.

- 3). Non-preemptive constraint: As connection requests arrive in the network at different times, we assume that the connections established later cannot disturb existing connections, that is, no rerouting of existing connections is allowed.
- 4). Wavelength continuity constraint: Because wavelength conversion cannot occur at the WSXCs, a lightpath must traverse on the same wavelength along its path. However, note that a connection may traverse several lightpaths on different wavelengths. This is because once a wavelength (corresponding to a lightpath) is dropped from a WSXC to its attached IP/MPLS router (or SADM) at the destination node of the corresponding lightpath, it will be processed in the electronic domain. If the node is not the destination for some connections groomed on the lightpath, they will be groomed to other lightpaths and retransmitted to their destinations. The lightpaths can use any wavelength available at the time when they are established.
- 5). Lightpath Capacity Constraint: The total bandwidth of all the connections carried over a lightpath must not be larger than the bandwidth of a lightpath.
- 6). Non-bifurcated routing constraint: We assume that the traffic belonging to the same connection request must be routed on the same path.

- **Objective**

The objective of the dynamic traffic grooming problem is to satisfy as many connections as possible in the network, that is, to maximize the network throughput or minimize the network blocking probability. As the connections are carried over the lightpaths, which comprise the virtual topology, one outcome of the traffic grooming problem is a virtual topology established over the physical topology. For dynamically arriving traffic, a fixed virtual topology may not be the best candidate for the sets of connections at different times. In this paper, we assume an automatically evolving strategy for the virtual topology. Initially when there is no connection, the virtual topology is empty. When connections arrive, lightpaths are established to carry those connections. As a connection may use only a small part of the bandwidth of a lightpath, other connections may be groomed on the lightpath later. If some connections depart and no

connection uses a lightpath, the lightpath is torn down and its resources are released. Note that to support such an automatically evolving strategy, the underlying optical network should be automatically reconfigurable. With the advances of intelligent switching technologies such as automatically switched optical networks (ASONS) [21][22][23] and generalized multi-protocol label switching (GMPLS) [24], it is reasonable to assume that future optical networks will have dynamic provisioning capability.

### 3. Grooming Heuristic and Policies

Using fixed alternate routing, multiple candidate paths are identified for each node pair. As illustrated in Fig. 3, for each candidate path, there are multiple candidate routes depending on the selection of grooming nodes on the candidate path. Note that a route is a path with some nodes designated as grooming nodes (see Fig. 3). The grooming node selection problem on a path is called as route selection problem in this paper and it is determined by the grooming policies which will be introduced in section III.B. In section III.A, we propose the fixed-order grooming (FOG) algorithm which assumes the order of the candidate routes is already determined by a specific grooming policy.

#### 3.1. Fixed-Order Grooming (FOG) Algorithm

Before the introduction of the FOG algorithm, we first describe the categories of routes. According to the hop count of a route and whether new lightpaths need to be established in the route, there are basically four categories of routes, as illustrated in Fig. 4.

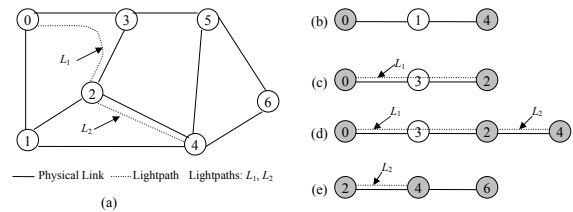


Fig. 4. Illustration of route categories. (a) The physical topology of a network and two lightpaths established on the physical topology, (b) A SN-route, (c) A SE-route, (d) An MOE-route, (e) An MNE-route.

- 1). Single-hop route using a new lightpath (SN-route). For example, for a connection request from 0 to 4, suppose the route in Fig. 4 (b) is the current candidate route, then it is a SN-route if a new lightpath is established on the path 0-1-4 to satisfy the connection.
- 2). Single-hop route using existing lightpath (SE-route). For example, for a connection request from 0 to 2, suppose the route in Fig. 4 (c) is the current candidate

route, then it is a SE-route if the existing lightpath  $L_1$  on path 0-3-2 is used to satisfy the connection.

- 3). Multi-hop route only using existing lightpaths (MOE-route). For example, for a connection request from 0 to 4, suppose the route in Fig. 4 (d) is the current candidate route, then it is an MOE-route if the existing lightpaths  $L_1$  and  $L_2$  are used to satisfy the connection.
- 4). Multi-hop route using new lightpaths (MNE-route). For example, for a connection request from 2 to 6, suppose the route in Fig. 4 (e) is the current candidate route, then it is an MNE-route if a new lightpath on path 4-6 has to be established to satisfy the connection, even though the connection still uses the existing lightpath  $L_2$ .

Note that a single-hop route can be both an SN-route and an SE-route if both a new lightpath and an existing lightpath can be used to carry the connection. The same situation exists for multi-hop routes. Therefore, it is up to the grooming algorithm as to decide which one to use. The FOG grooming algorithm in Fig. 5 always prefers existing lightpaths over new lightpaths when faced with such choices.

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#### Algorithm FOG

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*Input:* A connection request  $(s, d, \delta)$ , physical topology  $G_p$ , wavelength and transceiver usage information, virtual topology  $G_v$ , and lightpath usage information. The candidate paths between all node pairs are pre-computed. The order of the candidate routes on these candidate paths is also pre-determined by the grooming policies used.

*Output:* A connection route  $r^*$ .

- 1) **for** each candidate route  $r$  from node  $s$  to node  $d$  **do**
  - 2)      $r^* \leftarrow r$
  - 3)     **for** each hop  $h$  (a sub-path  $p_s$ ) in route  $r$  **do**
  - 4)         **if** (an existing lightpath on  $p_s$  has more than  $\delta$  unit of free bandwidth) **then**  
                **continue;**  
                **else if** (there is free wavelength and transceiver on  $p_s$  to establish a new lightpath) **then**  
                    **continue;**  
                **else**  
                     $r^* \leftarrow \text{NULL};$   
                    **break;**
  - 5)     **if** ( $r^*$ ) **then**  
            Establish new lightpaths if necessary. Then establish a connection on route  $r^*$ .  
            **return**  $r^*$ .
  - 6) **return**  $\text{NULL};$
- 

Fig. 5. The FOG grooming algorithm.

### 3.2. Grooming Policies

As introduced in section I, an  $H$ -hop path can generate at most  $2^{H-1}$  different routes. As the number of candidate routes increases exponentially with the number of hop within a path, it is impractical to search all the candidate

routes in a large network. One way to limit the number of candidate routes is to set up a limit on the number of hops a route can take. For example, if we limit the maximum number of hops in a route to 2, then an  $H$ -hop path can have one ( $C_0^{H-1}$ ) direct route and at most  $C_1^{H-1}$  2-hop routes. The total number of candidate routes is  $C_0^{H-1} + C_1^{H-1} = H$ . Another way to reduce the number of candidate routes is to selectively search some candidate paths, instead of exhaustively searching all possible routes.

In addition to the number of candidate paths, another factor affecting the results of the grooming algorithm is the order of the candidate routes. In this section, we propose several grooming policies which address the candidate route selection and ordering problems.

#### 3.2.1 Load Sharing (LS), Sequential Grooming (SG) and Minimum Gap (MG)

- Load sharing (LS): For an  $H$ -Hop path, the LS grooming policy first tries to satisfy a connection using the direct route. If the direct route cannot satisfy the connection, then a two-hop candidate route is randomly selected from all the  $C_1^{H-1}$  2-hop routes on the path. If the 2-hop candidate route cannot satisfy the connection, then a 3-hop candidate route is randomly selected from all the  $C_2^{H-1}$  3-hop routes. The process continues until the connection is satisfied or the maximum number of route hops reaches the limit.
- Sequential Grooming (SG): For an  $H$ -Hop path, the SG grooming policy first tries to satisfy a connection using the direct route. If the direct route cannot satisfy the connection, then the 2-hop routes on the path are tried one by one to satisfy the connection. If the 2-hop candidate routes still cannot satisfy the connection, then the 3-hop routes are tried one by one to satisfy the connection. The process continues until the connection is satisfied or the maximum number of route hops reaches the limit.
- Minimum Gap (MG): A gap is a hop in a route where there is no existing lightpath on this hop. The length of a gap is the number of physical hops contained in this gap. A route may have several gaps and the total gap length of a route is the sum of the lengths of all the gaps in this route. Unlike the SG grooming policy, which stops once a feasible route is found, the MG grooming policy continues to evaluate all the candidate routes and finally selects the one with the minimum number of gaps. If two candidate routes have the same number of gaps, the one with the shorter total gap length is selected.

Among the three grooming policies, LS should have a lower time complexity because it only considers a small portion of all the possible routes, while SG and MG should have better blocking performance because they consider all the possible routes under the hop limit.

Usually, more candidate routes for a connection imply a larger probability that the connection will be accepted.

### 3.2.2. Least Physical Hop (LPH) first, Least Virtual Hop (LVH) first and Least Stringent Resource (LSR) first

Two major resource constraints in an optical grooming network are due to wavelengths and transceivers. Therefore, to save wavelength resources, the traffic grooming algorithm should use a route with the shortest physical length (or the least number of physical hops) to satisfy a connection. On the other hand, to save transceiver resources, the traffic grooming algorithm should use a route with the least number of virtual hops (lightpaths) to satisfy a connection. This is because each lightpath uses a transmitter/receiver pair. The more lightpaths a route uses, the more transceiver resources it uses. For example, a 2-hop route on a path uses twice the amount of transceiver resources than a direct route on the same path, although the two routes use the same amount of wavelength resources.

To address the two constraints, we propose the least physical hop first (LPH) and least virtual hop first (LVH) grooming policies. The LPH grooming policy favors a route with fewer physical hops over a route with more physical hops, even though the latter may have fewer virtual hops than the former. If both routes have the same number of physical hops, the LPH grooming policy favors the route with fewer virtual hops. The LVH grooming policy, on the other hand, prefers a route with fewer virtual hops over a route with more virtual hops, even though the latter may have fewer physical hops than the former. If both routes have the same number of virtual hops, the LVH grooming policy selects the route with fewer physical hops. Fig. 6 shows an example of how to order the candidate routes when LPH or LVH is used.

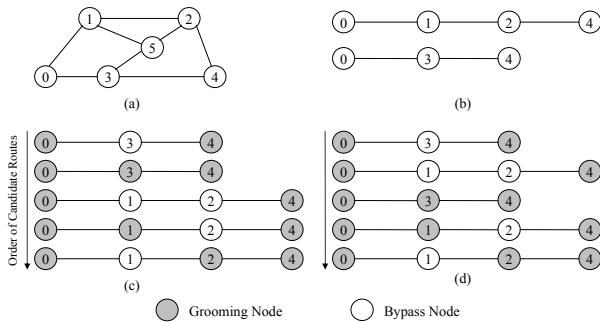


Fig. 6. Illustration of the LPH and LVH grooming policies. Assume that a route can have at most two virtual hops. (a) The physical topology of a 6-node network, (b) Two candidate paths from node 0 to node 4, (c) The order of candidate routes on the two candidate paths if LPH grooming policy is used, (d) The order of candidate routes on the two candidate paths if LVH grooming policy is used.

With LPH and LVH probably suited for a wavelength stringent situation and a transceiver stringent situation respectively, the least stringent resource (LSR) grooming policy tries to combine the advantages of both LPH and LVH. If the average utilization of wavelengths in the network is larger than the average utilization of transceivers, the situation is said as wavelength stringent. Otherwise, the situation is said as transceiver stringent. In wavelength stringent case, the LSR grooming policy will use exactly the LPH grooming policy, while in transceiver stringent case, it will use the LVH grooming policy. In situations where the utilizations of the wavelengths and transceivers are close, the LSR grooming policy may flip-flop between LPH and LVH.

While the grooming policies LS, SG and MG largely determine the candidate route space, the grooming policies LPH, LVH and LSR mainly determine the order of the candidate routes in the candidate route space. Therefore, a complete grooming policy should use exactly one grooming policy from each of the two categories of grooming policies. For example, using SG together with LPH is one of nine possible choices provided in this paper. Actually, the example in Fig. 6 assumes the SG grooming policy. If the LS grooming policy is used in Fig. 6, then only one of the two 2-hop routes on path 0-1-2-4 can be used as a candidate route.

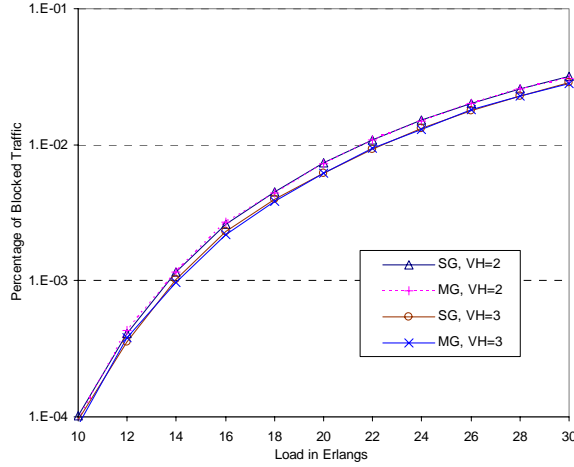
## 4. Numerical Results

To evaluate the performance of the grooming policies, we simulate them on the NSFNET network and the EUPAN network as shown in Fig. 7. The following assumptions are used in our simulation: The arrival of connection requests on each node is a Poisson process with rate  $\lambda$ . The connection requests arriving at a node are uniformly destined to all the other nodes. The service time of the connection requests is exponentially distributed with unit mean. We assume that the capacity of a lightpath is  $OC-48$ , and the set of connections rates is  $\{OC-3, OC-12, OC-48\}$ . Using normalization, we can obtain the grooming factor  $C = 48/3 = 16$ . And the set of connection rates becomes  $X = \{1, 4, 16\}$  after normalization. We assume that connections at each rate request the same amount of total bandwidth, that is, the probability that an arriving connection request is at rate  $x$  is  $\frac{1/x}{\sum_{x \in X} 1/x}$ . We simulate 1,000,000 connection requests for each scenario in this section.

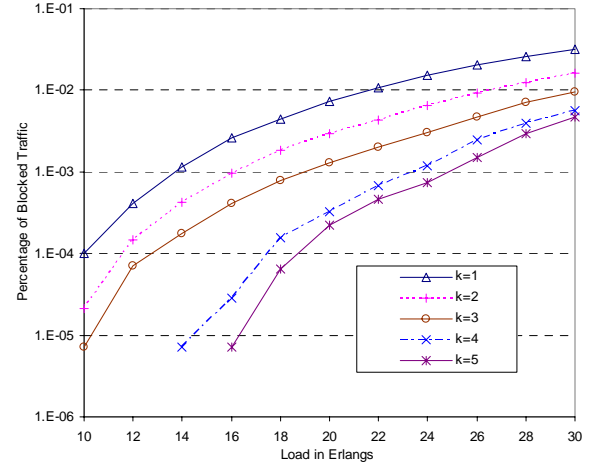
### 4.1. Single Hop Grooming vs Multi-Hop Grooming

Fig. 8 shows the effect of the number of virtual hops

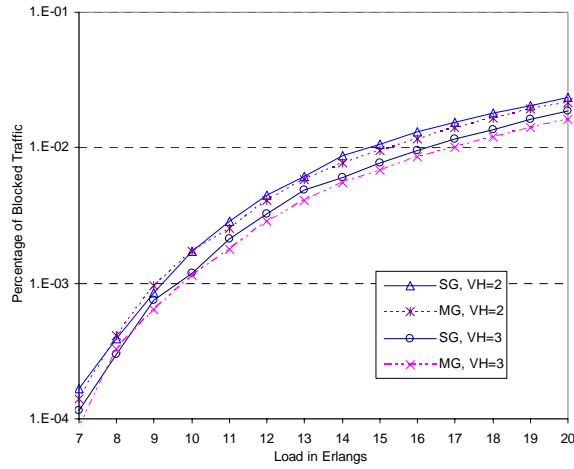




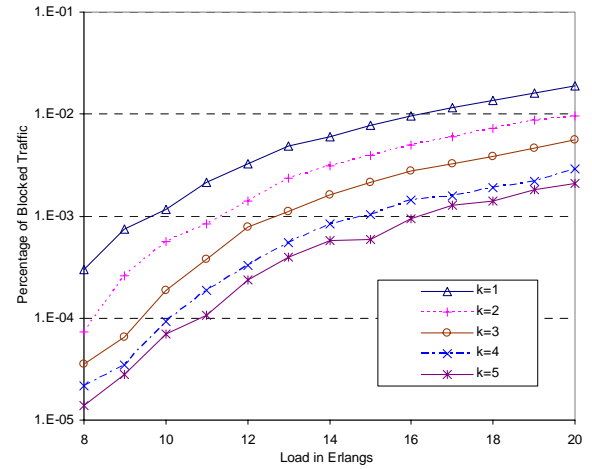
(a)



(a)



(b)



(b)

Fig. 9. Sequential grooming (SG) vs Minimum Gap (MG). (a) Results for the NSFNET network with 16 wavelengths each link and 32 transceivers each node, (b) Results for the EUPAN network with 20 wavelength each link and 32 transceivers each node. The acronym VH represents the limit to the maximum number of virtual hops within a route.

Fig. 10. The effect of the number of alternate paths on the blocking performance. The SG and LPH grooming policies are used. The number  $k$  is the maximum number of alternate paths used for each node pair. (a) Results for the NSFNET network with 16 wavelengths each link and 32 transceivers each node, VH=2, (b) Results for the EUPAN network with 20 wavelength each link and 32 transceivers each node, VH=3.

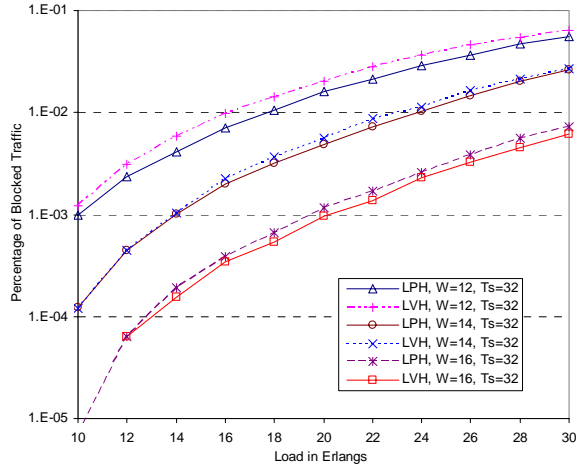
### 4.3. The Effect of the Number of Alternate Paths on the Blocking Performance

Fig. 10 shows the effect of the number of alternate paths ( $k$ ) on the blocking performance of the grooming algorithm. Note that the alternate paths are not necessarily link-disjoint. As can be seen, the parameter  $k$  has significant impact on the performance of the grooming algorithm. The blocking performance improves when the parameter  $k$  increases.

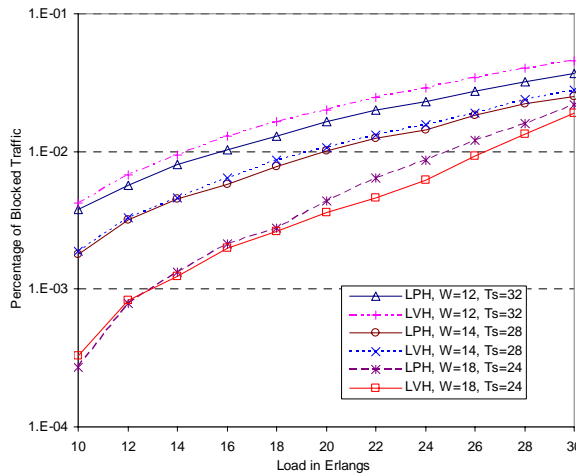
### 4.4. Least Physical Hop (LPH) vs Least Virtual Hop (LVH)

Fig. 11 shows that the LPH generally performs better

in wavelength stringent situations, while LVH generally performs better in transceiver stringent situations. For example, in Fig. 11 (a), when there are only 12 wavelengths on each link, LPH obviously outperforms LVH. LPH still outperforms LVH when there are 14 wavelengths on each link. But the blocking probability difference between LPH and LVH decreases compared with that with 12 wavelengths. When there are 16 wavelengths on each link, LVH outperforms LPH. For another example, in Fig. 11 (b), with wavelength per link at 12 and transceiver per node at 32, wavelength resource is the relatively stringent resource. LPH outperforms LVH in this case. When wavelength per link is at 18 and transceiver per node is at 24, transceiver resource becomes the relatively stringent resource. In this case,



(a)

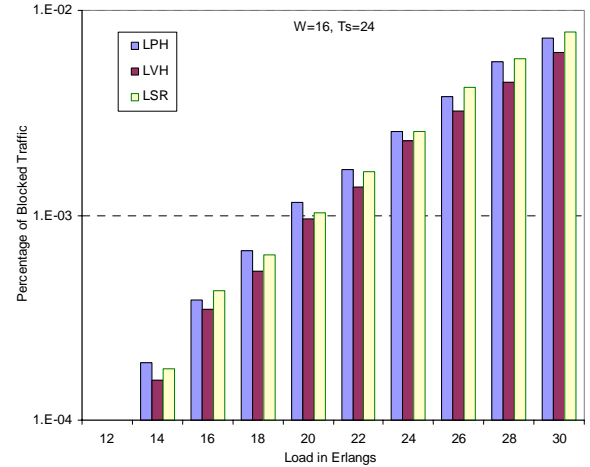


(b)

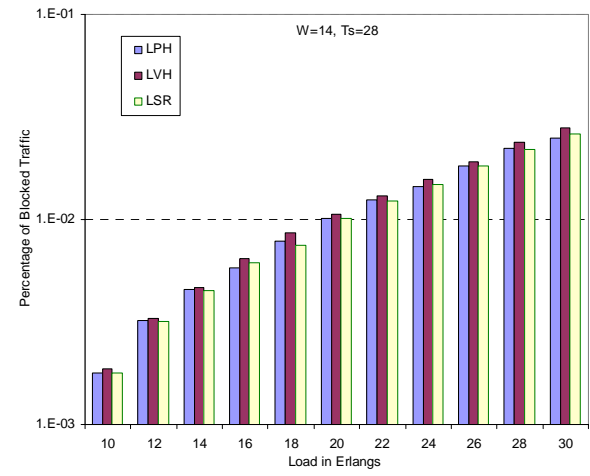
Fig. 11. LPH vs. LVH. The SG grooming policy is assumed. The maximum number of virtual hops within a route is set to 3.  $W$  is the number of wavelengths supported on each link and  $T_s$  is the number of transceivers on each node. (a) Results for the NSFNET network,  $k=3$ , (b) Results for the EUPAN network,  $k=5$ .

LVH outperforms LPH. For the intermediate case with wavelength per link at 14 and transceiver per node at 28, LPH and LVH have almost the same performance.

As for the LSR grooming policy, it is almost certain that it will have the same blocking performance as LPH in obviously wavelength stringent situations, and it will have the same blocking performance as LVH in obviously transceiver stringent situations. However, in those intermediate situations where utilizations of wavelengths and transceivers are quite close, the performance of the LSR grooming policy remains to be seen. Fig. 12 compares LSR with LPH and LVH in terms of blocking performance in those “close” situations. As can be seen, LSR displays a mixed performance compared with LPH and LVH. Sometimes it is even worse than both LPH and LVH. However, in most cases, it is at least better than one



(a)



(b)

Fig. 12. LSR vs LPH and LVH. The SG grooming policy is assumed. The maximum number of virtual hops within a route is set to 3.  $W$  is the number of wavelengths supported on each link and  $T_s$  is the number of transceivers on each node. (a) Results for the NSFNET network,  $k=3$ , (b) Results for the EUPAN network,  $k=5$ .

of LPH and LVH. This is especially obvious in Fig. 12 (b). Generally, in those “close” situations, the blocking performance of the three grooming policies are also quite close. No one grooming policy performs obviously better than the other two.

## 5. Conclusions

In this paper, we studied dynamic traffic grooming in WDM mesh optical networks using fixed-alternate routing. We first proposed the FOG grooming algorithm which supports on-line provisioning of multi-granularity sub-wavelength connections. Based on the two-layered routing characteristic of the traffic grooming problem, we introduced the route selection problem (or grooming node selection problem) on the candidate paths. To address the

route selection problem, we proposed three grooming policies which include load sharing (LS), sequential grooming (SG) and minimum gap (MG). We proposed three other grooming policies, least physical hop first (LPH), least virtual hop first (LVH) and least stringent resource first (LSR), to address the wavelength and transceiver constraints in grooming networks. Numerical results show that multi-hop traffic grooming obviously outperforms single-hop traffic grooming. Generally, the more number of hops allowed in a route, the better performance the FOG grooming algorithm can achieve. The MG grooming policy outperforms the SG grooming policy in most cases and the latter generally outperforms the LS grooming policy. However, the LS grooming policy can achieve a comparable performance with the SG grooming policy when the number of hops allowed in a route becomes relatively large. The numerical results also show that LPH outperforms LVH in obviously wavelength limited situations and LVH outperforms LPH in obviously transceiver limited situations. LSR has the same performance as the better one between LPH and LVH in those cases. However, in the intermediate situations where the utilizations of wavelengths and transceivers are close, none of the three grooming policies always outperforms the other two. Finally, our results show that the number of alternate paths has a significant impact on the blocking performance of the grooming algorithms.

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