Efficient Online Traffic Grooming Algorithms in WDM Mesh Networks with Drop-and-Continue Node Architecture

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Abstract

As high capacity all-optical networks and WDM technologies advance and merge together, aggregating low-speed traffic streams onto high-speed wavelengths becomes more critical. Efficient aggregation techniques, known as traffic grooming, allow higher bandwidth utilization and can reduce request blocking probability. These algorithms can also result in lower network cost in terms of electronic switching. In this paper we focus on traffic grooming in WDM mesh networks with dynamic traffic patterns. We offer two new grooming concepts called lightpath dropping and lightpath extension. These concepts are based on an alternative node architecture in which incoming optical signals can be dropped at a node, while optically continuing to the next node. Based on these concepts, we develop several grooming algorithms and study them under various network objectives. We also compare their performance with previously proposed lightpath-based grooming algorithms. Through extensive simulation results we show that our proposed approaches lead to lower request blocking probability and lower average number of logical hops when the number of transceivers per node is limited.

Keywords: *Lightpath, optimization algorithms, traffic grooming, WDM mesh networks*

1 Introduction

Wavelength division multiplexing (WDM) technology offers a viable solution to fully exploit the enormous bandwidth available in fiber optics and is rapidly becoming the dominant transport infrastructure for future telecommunication networks. An attractive feature of this technology is its ability to economically and rapidly increase the transmission capacity of a single optical fiber. Currently, available WDM systems support from 32 to 64 channels per fiber, and vendors are promising 96 to 128 channel systems in the coming years. At the same time, researchers are developing WDM systems with 256 and higher wavelengths channels offering multi-Tera-b/s capacity.

Recently, considerable attention has been given to combining WDM technology with evolving all-optical backbone networks. By merging WDM technology and optical cross-connects, individual wavelength channels can be set up between a source and a destination node, while optically passing through intermediate nodes. Such all-optical communication channels are called *lightpaths* [1]. Generally, lightpaths offer much higher capacity than the bandwidth required by individual users. For example, a lightpath can offer an available bandwidth of 10 or 40 Gb/s, whereas a single client typically requires a fraction of this bandwidth. Therefore, aggregating several low-bandwidth data streams into high-capacity lightpaths can provide efficient bandwidth utilization, which in turn reduces the network cost. The problem of multiplexing and routing low-speed traffic requests over lightpaths, as well as determining their wavelength assignments, is known as the *traffic grooming problem*. It has been shown that the general problem of traffic grooming with arbitrary traffic is NP-complete [2]. Heuristic algorithms that attempt to solve the traffic grooming problem are referred as *grooming algorithms*. Depending on the network assumptions and constraints, grooming algorithms can consider different routing criteria. We refer to such criteria as *grooming policies*. For example, in order to satisfy new requests, the grooming policy can be based on finding the shortest physical route in which we attempt to maximize wavelength utilization.

The traffic grooming problem has been studied for a wide range of multi-layer networks, including SONET over WDM or IP with Multi-Protocol Label Switching (IP/MPLS) over WDM. In [3], the authors consider the problem of traffic grooming for IP over WDM optical networks to bridge the routing and resource allocation between the IP and optical networks. With advances in GMPLS technology, grooming a set of Label Switched Paths (LSPs) into lightpaths for transport over a wavelength-routed network has also been studied [4]. Broadly speaking, however, traffic grooming studies can be categorized by the way in which they define the network topology (ring, mesh, etc.), the traffic scenario (static or dynamic), and the solution approach, such as providing a linear program formulation, or finding upper/lower bounds, or proposing heuristics algorithms. A comprehensive survey of the work done on traffic grooming in ring WDM networks is provided in [5].

Much work has focused on traffic grooming in SONET/WDM networks with ring topologies under a static traffic scenario, where the traffic pattern is known in advance. The main objective in these studies is to minimize the network equipment cost. In [2], the authors provide a lower bound on the number of required SONET add-drop multiplexers (ADMs) and present a heuristic algorithm that performs closely to the bound. In [6] the objective is to minimize the number of ADMs, and in [7] minimizing the electronic switching cost is the main concern. An overview of studies on grooming in SONET/WDM ring networks can be found in [8].

Traffic grooming has also been studied for WDM mesh topologies when the traffic matrix is known in advance. In [9] an integer linear programming (ILP) optimization approach and some heuristics have been proposed to increase the network throughput. A different study in [10] proposes a two-layered traffic grooming heuristic algorithm which attempts to reduce the overall network cost.

In recent years, research on traffic grooming in WDM mesh optical networks with dynamic traffic demands has also received some attention. Under a dynamic traffic scenario, requests randomly arrive or leave and lightpaths are dynamically set up or torn down. In [11] -[12] the authors propose several grooming algorithms in order to reduce the request blocking probability. A performance analysis model for a single-hop dynamic traffic grooming algorithm in WDM mesh optical networks is presented in [13].

All these previous works are based on the assumption that a node can either drop or pass-through an incoming lightpath, as described in [14]. Our study, on the other hand, is based on an alternative node architecture in which incoming lightpaths can be dropped and continue travelling to the next node, optically. Under this assumption, we address the problem of the dynamic traffic grooming in wavelength-routed WDM mesh networks and attempt to minimize the connection request blocking probability. The main contribution of this paper is to introduce two new grooming concepts called lightpath dropping and lightpath extension. The basic underlying principle in lightpath dropping is that a lightpath can be dropped at its intermediate nodes, while continuing its path to the end node, optically. On the other hand, in lightpath extension, the basic idea is that a lightpath can be extended optically beyond its original end node. Based on lightpath dropping and extension concepts, we propose several grooming algorithms to support dynamic unicast traffic scenarios. We also develop an auxiliary graph model through which we implement our proposed algorithms. In our model, the grooming problem is solved by simply applying the shortest-path computation method, and different grooming policies can be represented by different weight-assignment functions. Using simulation techniques we examine the performance of our proposed grooming algorithms under specific network conditions. We compare our results with those obtained by other traffic grooming approaches, such as [11] and [12], in terms of blocking probability and average number of logical hops. We show that our proposed approaches lead to better performance when the number of transceivers is limited.

The rest of this paper is organized as follows. In Section 2, we propose a two-layered node architecture in which optical signals can drop and continue along their optical path. In Section 3, we formulate the grooming problem and identify our basic network assumptions. In this section, we also introduce our proposed grooming algorithms in details. In Section 4, we discuss a case study and provide our simulation results. Section 5 concludes the paper.

2 Node architecture

A general architecture of a WDM node with optical cross-connect and electronic grooming capacity is shown in Fig. 1(a). This is a two-layered architecture consisting of photonic and electronic layers. The optical cross-connect (OXC) is the core of the photonic layer. It receives W wavelengths from each of P input fibers and switches them optically to wavelengths on the appropriate output ports. The OXC may be equipped with wavelength converters, in which case incoming light can change color before continuing to the next node. More sophisticated architectures allow waveband-switching in which a group of wavelengths can switch together [15].

In a WDM network, a node can function as a *transparent* or an *opaque* node. In a transparent node all wavelength channels are optically switched, whereas in an opaque node wavelength channels are terminated and undergo electronic processing and switching. A *translucent* node is transparent with respect to some of the optical data channels and opaque with respect to others.

The electronic layer of the WDM node, as shown in Fig. 1(a), consists of optical-electronic-optical (OEO) converters, multiplexers and demultiplexers, and the grooming switch fabric. Each multiplexer and demultiplexer consists of one or more transmitters and receivers, respectively. A transmitter (receiver) is connected to an add (a drop) port on the OXC and allows the lower rate signals to be inserted into (extracted from) the high-speed optical signals. The main cost of the WDM node is due to its electronic layer, both in terms of add-drop capacity and *grooming granularity*, g. We define the grooming granularity as the lowest rate at which the equipment can carry, switch, multiplex, and demultiplex signals. For example, consider a node with full add-drop capacity, where all incoming wavelengths can be dropped, $g = 16$, and wavelengths are operating at OC-192 rates. In this case, each node will require $P \cdot W$ transmitters and receivers and an electronic switch fabric with $g \cdot P \cdot W$ inputs operating at OC-12 rates (recall, OC-192 = 10 Gb/s and OC-12 = 622 Mb/s).

We consider translucent nodes where optical cross-connects can have two distinct capabilities: *Terminate-or-Continue* and *Drop-and-Continue*. Optical cross-connects with terminate-or-continue (TOC) capacity, as shown in Fig. 1(b), can either terminate the incoming lightpath *or* allow the incoming lightpath to optically bypass the node. In such architectures, lightpaths are established between source-destination node pairs and cannot be directly utilized by intermediate nodes. At the destination node, the dropped traffic can be *fully* or *partially* switched to local clients. When partially switched, the remaining lightpath traffic can be aggregated with other incoming or local traffic and retransmitted to the next node. Note that the retransmitted traffic can be carried to the next node on a different wavelength.

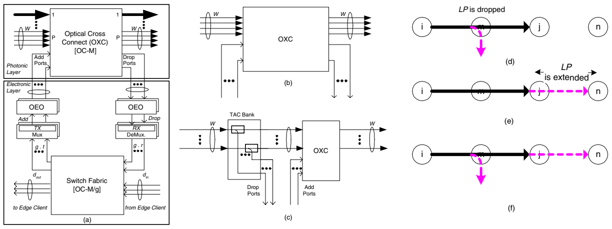


Figure 1: (a) A two-layered WDM node architecture; (b) terminate-or-continue (TOC) optical cross-connect; (c) drop-and-continue (DAC) optical cross-connect with tap-and-continue (DAC) optical devices. A network of nodes with DAC-based OXC architecture can perform the following operations: (d) lightpath dropping on an intermediate node; (e) lightpath extension to the next node; (f) lightpath dropping and lightpath extension.

In a drop-and-continue (DAC) optical cross-connect, shown in Fig. 1(c), incoming optical signals can be split unequally. Consequently, a small portion of the optical signal can be dropped and processed electronically, while the remaining portion continues to travel optically to the next node with negligible degradation [16]. Such optical power splitting can be achieved by passive devices called *tap-and-continue*. The main advantage of the DAC optical cross-connect architecture is that it allows an available lightpath to be shared by connection requests whose destinations are intermediate or end nodes of the lightpath. However, a potential drawback of this architecture is the excessive power loss that a lightpath may experience as it passes through many nodes. Due to lack of space, in this study we ignore power considerations and assume power loss in each node is negligible.

Lightpath dropping and lightpath extension concepts can be supported using the DAC-based OXC architecture. Fig. 1(d) shows a network of DAC-based nodes where the bypassing lightpath is dropped at an intermediate node, while the end node of the lightpath remains the same. The DAC-based nodes also allow a terminated lightpath to extend beyond its original terminating node. This is shown in Fig. 1(e). Lightpath dropping and lightpath extension concepts can be implemented together, as shown in Fig. 1(f). In this case, the DAC-based nodes can drop the incoming lightpath on one or more intermediate nodes, while the lightpath is optically extended to the next node.

3 Problem formulation and description of grooming algorithms

In this section we first formulate the grooming problem and then describe our proposed grooming algorithms.

3.1 Problem formulation

We formulate the traffic grooming problem as follows: Given the physical network topology, number of wavelengths on each fiber, number of transceivers at each node, and the incoming request's information (including its bandwidth demand requirement, granularity of traffic, connection duration, and source-destination node pair) find the routing for the incoming connection request such that the blocking probability is minimized.

In this context, we consider the following assumptions:

- all requests are unicast with sub-wavelength bandwidth requirements and random arrivals and departures;
- all nodes have full grooming capability and DAC-based OXC architecture with no wavelength converters;
- all transmitters and receivers are tunable to all wavelengths;
- connection requests can be realized using multi-hop or single-hop routing;
- a connection request will be blocked when no wavelength channel with sufficient bandwidth is available.

The routing criteria, which determine how a connection request should be established, directly impact the average number of transmitters and receivers required in each node, and thus affect the overall cost of electronics in the network. For example, consider a case in which a connection request can be established using an existing and a new lightpath. In this case, each of the two lightpaths requires a transmitter and a receiver. However, if the existing lightpath can be extended using a DAC-based node architecture, a single transmitter will be sufficient to satisfy multiple requests.

3.2 Previous work

In terms of aggregating sub-wavelength connection requests, existing approaches can be divided into two basic categories: link-based and lightpath-based. In the link-based approach (LBA), optical paths are only established between adjacent nodes, and the optical paths can support multiple requests with sub-wavelength demands. Thus, the LBA simply involves finding the shortest physical path for each connection request and requires no wavelength routing [17]. It can be seen that when all nodes have a sufficient number of transmitters and receivers, the LBA can result in a very efficient bandwidth utilization and low request blocking probability. However, LBA's tradeoff is its high cost of electronics.

In lightpath-based grooming approaches, multiple connection requests with sub-wavelength demands can share the same lightpath between a source-destination node pair. Different grooming approaches have been considered to aggregate multiple requests in a single lightpath. One simple approach, known as single-hop end-to-end grooming, is based on establishing dedicated lightpaths to satisfy requests with the same source-destination nodes [18]. Hence, in this case, all intermediate nodes are transparent to the incoming optical data. Note that, in this approach, wavelength routing and wavelength assignment are limited to finding an available wavelength on the shortest path between the source and destination node. The tradeoff to the simplicity of the single-hop end-to-end grooming approach is its inefficiency and low wavelength utilization.

A widely considered lightpath-based traffic grooming is a multi-hop approach in which requests share a single or multiple lightpaths to reach their destination nodes. In this approach, once a lightpath is established, its source and destination nodes cannot be modified until all its embedded requests are serviced. Furthermore, in this approach, the intermediate nodes along the lightpath cannot receive or transmit new data into the lightpath unless the new data is sent to the lightpath's source node. Different grooming policies can be applied to the multi-hop lightpath-based algorithm (recall that grooming policies determine how to route and aggregate connection requests in the network). Three typical grooming policies are as follows: (1) minimizing the logical hop-length; (2) minimizing the physical hop-length; and (3) minimizing new lightpath setup. Logical hop-length of a route is the total number of logical links traversed by that route. On the other hand, physical hop-length of a logical link is the total number of physical links (fibers) traversed by that logical link. Minimizing the new lightpath setup involves utilizing existing lightpaths prior to establishing new ones.

The single-hop end-to-end and multi-hop lightpath-based grooming algorithms are based on a terminate-or-continue optical cross-connect architecture, as shown in Fig. 1(b). In this architecture, a node can either drop *or* pass-through the incoming traffic. Once a lightpath is dropped and electronically switched at a node, it is possible that some of its embedded requests are retransmitted to the next node.

3.3 Algorithms

In this section we introduce our proposed lightpath-based algorithms, in which lightpaths can dynamically be dropped at multiple nodes as new unicast connection requests arrive. We distinguish these algorithms based on their capability to perform one or both of the following operations:

- Dropping on intermediate nodes. In this case, the entire lightpath can be dropped at one or more intermediate nodes, while the end node of the lightpath remains the same.
- Extending beyond the original end node. In this case, while the incoming lightpath is still dropped at its original end node, the lightpath is optically extended to the next node.

The clear motivation in using our proposed algorithms is that when the number of transceivers is limited, the algorithms can provide significant improvement in terms of blocking probability and average number of logical hops over the traditional lightpath-based algorithms described above. In other words, for the same network performance, our proposed algorithms can significantly reduce the overall electronic cost throughout the network.

Intermediate dropping and lightpath extension capabilities can be supported by the drop-and-continue optical cross connect architecture, shown in Fig. 1(c). Recall that in such architectures, an incoming request can be dropped, passed-through, or dropped and continued to the next node.

We present an auxiliary graph to model the current state of the network. We use this graph model to implement our proposed grooming algorithms and examine their performance under different grooming policies. We begin by introducing the general case, in which dropping at intermediate nodes and lightpath extension are both allowed. Then, we discuss different variations of the general case where either intermediate dropping or lightpath extension is allowed.

3.3.1 Auxiliary graph model

Given a network with N nodes and W wavelengths per fiber link, the physical network can be represented by a graph $G_p = (V_p, E_p)$. In this representation, V_p is the set of network nodes, and E_p is the set of links connecting the nodes. The current status of the network can be modelled by a W-layer auxiliary grooming graph, $GG = (V, E)$, where each layer corresponds to the state of a wavelength in the network. A vertex $v \in V$ in the auxiliary graph, GG, represents the optical receiving or transmitting capabilities of a physical node on a particular wavelength layer. Therefore, a physical node can be represented by W receiving and W transmitting vertices.

On the other hand, E is a set of weighted directional edges which corresponds to available optical paths between node pairs. In our graph model, we define two basic edge types, namely, *grooming* edges and *optical* edges. A grooming edge abstracts the node's grooming capacity enabling an optical signal to be dropped and processed electronically. Therefore, for each physical node, there will be one grooming edge between a single receiving vertex and each transmitting vertex. We denote a grooming edge from a receiving vertex on layer x to a transmitting vertex on layer y on node i by $GP_i^{x,y}$.

An optical edge, on the other hand, represents an all-optical path between a node pair. Depending on the node architecture, in our graph model, we define the following optical edges, which can be established between a node pair (i, k) with one intermediate node j or more, on wavelength layer w:

- *Existing lightpath*, LP_{ik}^w, describing an active lightpath currently carrying traffic between nodes i and k;
- *Potential lightpath*, PLP_{ik}^w, representing one or more available wavelength links, which can support a new lightpath from node i to k;
- *Potential extended lightpath*, $PELP_{ik}^w$, expressing an existing lightpath, LP_{ij}^w, which can potentially traverse optically beyond its current end node, j, and reach node k through one or more available wavelength links;
- *Sub-lightpath*, SLP_{ij}^w, describing a possible optical connection between the source node, i, and an intermediate node, j, of the existing lightpath, LP_{ik}^w.

Note that for each existing lightpath with I intermediate nodes, there will be as many as I sub-lightpaths, all having the same free capacity. These concepts are illustrated in Fig. 2(a).

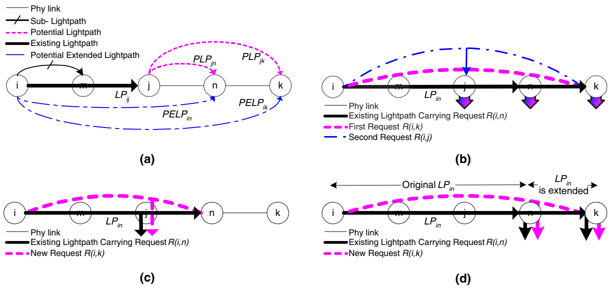


Figure 2: (a) Illustration of different optical edges used in the auxiliary graph; (b) The LPwDwE algorithm allows lightpath extension to node k and dropping on intermediate nodes j and n; (c) The LPwDnE algorithm allows a new request to share an existing lightpath while dropping on its intermediate node j; (d) Using the LPnDwE algorithm, a lightpath can be shared by multiple requests and extended beyond its original destination from node n to k.

3.3.2 Lightpath-based grooming with intermediate dropping and extension capacity (LPwDwE)

The LPwDwE algorithm supports two basic operations in order to route new connection requests: (1) existing lightpaths can be dropped at their intermediate nodes, while continuing their path to the end node; (2) existing lightpaths can be extended beyond their end nodes. These concepts are shown in Fig. 2(b). The main motivation for implementing the LPwDwE is to provide higher flexibility in finding the most appropriate routing path between a node pair.

The LPwDwE algorithm consists of two basic routines: *ReqSetup* and *ReqTeardown*. For each new connection request, the *ReqSetup* routine constructs a new auxiliary graph representing the current status of the network and finds the shortest path between the requested node pair. Details of the *ReqSetup* routine upon arrival of a new request $Req(s,d,B)$, where s and d are the source and destination nodes, respectively, and B is the request's demand, are described in Table 1.

Table 1: Algorithm description for the *ReqSetup* routine in LPwDwE.

For a given request $Req(s,d,B)$:

1. For each wavelength layer w and each node i on the physical graph G_p
    (a) Find the shortest path between node i and every other node j, such that a potentially new lightpath can be established between the two nodes, PLP_{ij}.
    (b) For every existing lightpath, between nodes i and j, LP_{ij}, with free capacity $C_f \geq B$,
        i. Find all possible sub-lightpaths between node i and all the intermediate nodes on LP_{ij}.
        ii. Find all possible potential lightpaths by extending LP_{ij} on available links.
    (c) Assign weight to all edges including potential lightpaths, potential extended lightpaths, existing lightpaths, sub-lightpaths, and grooming edges according to the grooming policy.
2. Search for the shortest path on the auxiliary graph between node s and d. If no such path was found, discard the request; otherwise, continue to next step.
3. Set up the route for the request $Req(s,d,B)$ and update the network status to reflect the latest connections and available resources.

On the other hand, when a request is completed the *ReqTeardown* routine is executed and operates as follows:

- *Step 1*: The request's demand is removed from all lightpaths carrying the request;
- *Step 2*: All *inactive* wavelength links along lightpaths carrying the request are removed. If all wavelength links on a lightpath are inactive, the entire lightpath will be removed;
- *Step 3*: The network state is updated accordingly to represent the latest available resources.

We illustrate the above concepts by means of an example. Fig. 3(a) shows a four-node network with four unidirectional fiber-links, each having two wavelengths. Each node is equipped with two transmitters and two receivers and has full-grooming capacity (the entire incoming data can be groomed). Initially, we assume that no connections exist in the network. Fig. 3(b) shows the current state of the network after a number of connection requests are established. Upon arrival of a new request, the auxiliary graph, shown in Fig. 3(c) can be established. We assume $LP^1_{3,4}$ and $LP^2_{4,1}$ have no available bandwidth and thus they are not shown in the auxiliary graph. Using the two available wavelength links between node pairs (2,3) and (3,4), we can generate 3 distinct potential lightpaths on Layer 2. The existing lightpath between node pair (1,2) can also be extended to Nodes 3 and 4. Furthermore, the existing lightpath on wavelength Layer 1 between Nodes 1 and 3 can support a sub-lightpath between node pairs (1,2), denoted by $SLP^1_{1,2}$. Let us assume that Node 3 requests a new connection to Node 2. Based on available resources, indicated by the auxiliary graph in Fig. 3(c), this request can be satisfied through the following shortest multi-hop path: $PLP^2_{3,4}$, $GP^{2,1}_4$, $LP^1_{4,1}$, $GP^{1,2}_1$, and $LP^2_{1,2}$.

The complexity of LPwDwE is mainly attributed to the *ReqSetup* routine, which in turn is directly tied to complexity of the shortest path algorithm. For example, assuming we implement Dijkstra's shortest path algorithm, the worst-case complexity of the *ReqSetup* will be equivalent to finding all available shortest paths between all nodes on all wavelength layers *and* the shortest path for the $Req(s,d,B)$ among all layers between the node pair (s,d). Thus, the worst-case complexity will be equivalent to $O(wn^3)+O((nw)^2)$. Note that if the number of wavelengths is much larger than the number of nodes in the network, as is the case in backbone networks with dense WDM links, the dominating factor will be $O((nw)^2)$.

As mentioned before, in the LPwDwE algorithm, an incoming connection request is routed according to the shortest path from its source to destination node in the auxiliary graph, GG. The weights assigned to different edges in the auxiliary graph determine how to route connection requests in the network. Such weight assignment is determined according to the grooming policy. In our study, we consider four grooming policies for the LPwDwE algorithm:

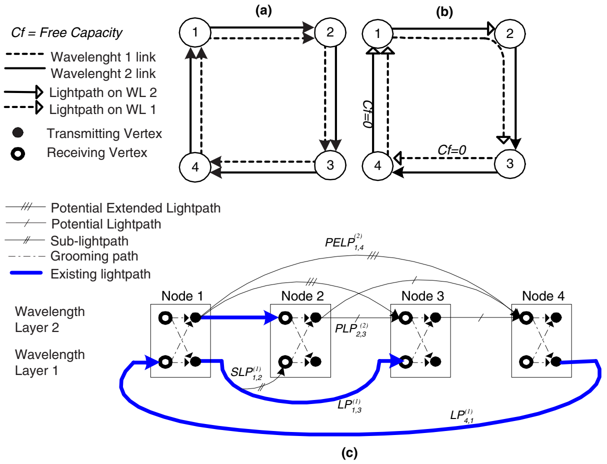


Figure 3: (a) An example of a four-node network with two wavelengths in each fiber; (b) the current state of the network with available wavelength links; (c) the auxiliary graph, GG, for the current state of the network shown in (b).

- Minimizing the number of logical hops (MLH). In this case the objective is to minimize electronic processing for connection requests. Therefore, the weight assignment for all optical edges will be the same.

- Minimizing the number of physical hops (MPH). Thus, the objective is to maximize wavelength utilization. The assigned weights to all optical edges must, therefore, be equivalent to the number of physical hops between the source-destination node pair.

- Minimizing the number of new lightpaths (MNL). The objective in this case is to minimize the number of transmitters and receivers. Thus, the existing lightpaths and potential extended lightpaths will have a much lower weight than new lightpaths.

- Minimizing the number of physical hops on lightpaths carrying the request (MTH). Thus, the objective is to maximize wavelength utilization. In this case, the weight assignment for all optical edges is equivalent to the number of physical hops on the entire edge, including the ones beyond the destination node.

Note that we distinguish between the MTH and MPH grooming policies because the number of physical hops between a node pair and the total number of physical hops along the single-hop or multi-hop lightpaths connecting the same node pair can be different. In general, grooming edges only abstract a node's grooming capacity, therefore, regardless of the grooming policy, their assigned weight is always much smaller than those of optical edges.

When multiple shortest paths are available for a connection request, it is efficient to choose a secondary objective to select the most appropriate available path. Therefore, in our graph model, we consider a primary and a secondary objective for each grooming policy. For example, when the primary objective is minimizing the number of logical hops and more than a single shortest route is available, we choose the route with the least number of physical hops.

3.3.3 Lightpath-based grooming with intermediate dropping capacity (LPwDnE)

The LPwDnE grooming algorithm can be achieved by allowing lightpaths to be dropped at any intermediate node. The motivation for implementing LPwDnE is to provide a flexible lightpath sharing mechanism. Details of the LPwDnE algorithm are similar to the *ReqSetup* and *ReqTeardown* routines described for the LPwDwE algorithm. However, since no lightpath extension is allowed in LPwDnE, Step 1-b(ii) in the *ReqSetup* routine will be eliminated. The basic operation of LPwDnE is illustrated in Fig. 2(c). Identical grooming policies and wavelength assignment criteria, as described for LPwDwE, are also applied for the LPwDnE algorithm.

3.3.4 Lightpath-based grooming with extension capacity(LPnDwE)

The basic idea in this traffic grooming algorithm is to allow the existing lightpaths to be extended optically on available wavelength links. When a lightpath is extended beyond its current end node, existing connections must not be interrupted. The basic operation of LPnDwE is shown in Fig. 2(d). A clear advantage of LPnDwE is reducing the number of logical hops between a node pair and thus lowering the total electronic equipment cost in the network. Similar steps described in the *ReqSetup* and *ReqTeardown* routines for LPwDwE, are used to implement the LPnDwE algorithm. However, since no intermediate dropping is allowed, Step 1-b(i) in the *ReqSetup* routine will be eliminated. All four grooming policies described for LPwDwE can also be applied to the LPnDwE algorithm.

3.3.5 Lightpath-based grooming with no intermediate dropping and no extension capacity (LPnDnE)

The LPnDnE is identical to the lightpath-based grooming approach described in other literature, including [11]. In this case, connection requests sharing a lightpath can only be dropped at the end node of the lightpath. In addition, once a lightpath is established, its source-destination nodes cannot be modified. We implement the LPnDnE algorithm using our proposed auxiliary graph. Upon request arrivals and departures, similar steps in the *ReqSetup* and *ReqTeardown* routines will be implemented, respectively. However, since no intermediate dropping or lightpath extension is supported by LPnDnE, in the *ReqSetup* routine, Step 1-b must be ignored. Similar weight assignments for implementing different grooming policies, as described for LPwDwE, are also applied to LPnDnE. Clearly, in LPnDnE, the MTH and MPH grooming policies will be identical.

4 PERFORMANCE COMPARISON

In this section we present the simulation results for each of the introduced grooming algorithms and compare their performances. We start by applying the proposed algorithms to a simple network.

4.1 Numerical Comparison Between Different Algorithms

Fig. 4(a) shows a 7-node network with unidirectional fiber links, each having unity length and a single wavelength. We consider implementing the following grooming algorithms: LBA, LPnDnE, LPwDnE, LPnDwE, and LPwDwE for a series of incoming requests. For each case we intend to determine the total request blocking and average number of logical hops.

In this example, each node is assumed to have 7 receivers and transmitters and we consider minimizing the number of logical hops as the grooming policy. We also assume that initially, at T_0 , all links in the network are available and new requests arrive between T_1 and T_8 in the following order: (0,2),(4,3),(4,2),(1,5),(1,6). Each request has a demand equivalent to 1/4 of the wavelength capacity and a duration longer than T_8. First, we implement the link-based algorithm (LBA) where optical paths are established only between adjacent nodes. In this case, each connection request is satisfied by finding the shortest path between its source and destination nodes. The average number of logical hops is calculated to be 11/5. The resulting grooming solution is shown in Fig. 4(b). The request routing using the LPnDnE is shown in Fig. 4(c). In this case, two requests are blocked.

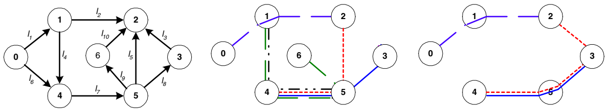
Fig. 4(d) shows the routing configuration resulted by implementing the LPwDnE algorithm. Notice that the request (1,6) is dropped at Node 4 and it is aggregated on the existing lightpath from Node 4 to Node 3. Although at Node 5 the entire lightpath is dropped, only request (1,6) is passed on to Node 6. Using the LPwDnE algorithm, all the requests are satisfied and compared to LBA, a relatively lower average hop distance can be achieved.

Routing requests using LPnDwE is shown in Fig. 4(e). Upon arrival, request (4,2) utilizes the existing lightpath between Nodes 4 and 3. Consequently, the lightpath will be extended to Node 2 and its available bandwidth is reduced by the latest request's demand. Using LPnDwE, only three of the requests can be satisfied, however, compared to LPnDnE a lower average hop distance can be archived.

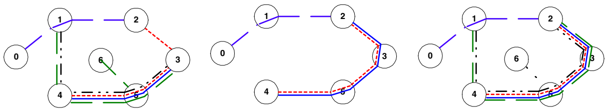
Finally, Fig. 4(f) shows the status of the network after routing all five requests using the LPwDwE algorithm. Similar to LPnDwE, upon receiving connection request (4,2), the lightpath between Nodes 4 and 3 is extended. In addition, since lightpath dropping on intermediate nodes is allowed, requests (1,5) and (1,6) can be carried over the existing lightpath and dropped at Node 5. LPwDwE satisfies all incoming requests with relatively lower average hop distance compared to LBA and LPnDnE. A quick look at Fig. 4 shows that LPwDwE requires the lowest total number of transmitters and receivers.

4.2 Simulation results

In this section we discuss some results obtained by implementing the proposed grooming algorithms, namely LPnDnE, LPnDwE, LPwDnE, and LPwDwE. We have chosen the NSFnet backbone, shown in Fig. 5, as our test network and consider the following assumptions for the simulation environment:



(a) Network topology (b) LBA: {(0,2),(4,3),(4,2),(1,5),(1,6)} (c) LPnDnE: {(0,2),(4,3),(4,2)}



(d) LPwDnE: {(0,2),(4,3),(4,2),(1,5),(1,6)} (e) LnDwE: {(0,2),(4,3),(4,2)} (f) LPwDwE: {(0,2),(4,3),(4,2),(1,5),(1,6)}

Figure 4: An example of a 7-node network topology and the grooming solution using different grooming algorithms. Incoming requests arrive in the following order: (0,2),(4,3),(4,2),(1,5),(1,6).

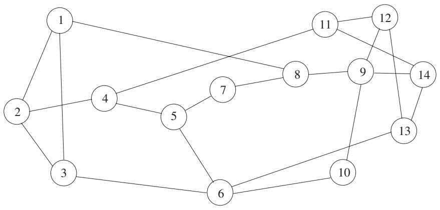


Figure 5: The NSF network with 14 nodes, 21 bi-directional links, and diameter of 3.

- The traffic requests are generated and terminated dynamically.
- Each link is bidirectional with *W=4* wavelenghts in each direction operating at OC-192 rate.
- All nodes have full grooming capacity with *r* receivers, *t* transmitters, and no wavelength-converters.
- Each request's demand can be one of the following rates: OC-3, OC-12, or OC-48.
- The traffic arrival is a Poisson process and the request's duration is exponentially distributed.

In this section we assume that traffic is uniformly distributed between all node pairs, and the number of transmitters and receivers per node is *r = 6* and *t = 4*, respectively.

Figs. 6-9 show the performance of each proposed algorithm under the following grooming policies: MPH, MLH, MNL, and MTH. It can be seen that regardless of the grooming policy, the best network performance in terms of request blocking probability is achieved by the LPwDwE algorithm. In fact, comparing the LPwDwE and LPnDnE algorithms, it is found that the former performs between 15 to 25 percent better, depending on the network load and grooming policy. This indicates that when a limited number of transmitters are available at each node, LPwDwE provides a more efficient lightpath sharing mechanism. The performance improvement of LPwDwE becomes less significant when the network load is very high and all resources are fully utilized, or when the network load is very low and a sufficient number of transmitters and receivers are always available to satisfy new requests. Under such extreme conditions, since network resources are either highly over-utilized or under-utilized, efficient bandwidth sharing does not significantly impact the blocking probability.

Further analysis show that depending on the grooming policy, the relative performance between the LPnDwE and LPPwDnE algorithms varies. Under MPH, MLH, and MTH, these algorithms perform similarly and they both outperform LPnDnE in terms of blocking probability, as well as the average number of logical hops. When the grooming policy is to minimize the number of new lightpaths (MNL), LPnDwE performs worse than LPwDnE and LPnDnE, as shown in Fig. 8. This can be explained by the fact that under MNL grooming policy, LPnDwE does not attempt to establish new lightpaths unless all existing lightpath capacities are exhausted. Thus, existing lightpaths continue to carry more connection requests and continue to extend, which in turn, potentially blocks more intermediate nodes from directly utilizing the wavelength channel.

Fig. 10 compares the average number of logical hops obtained by different grooming algorithms using the MTH grooming policy. Note that the average number of logical hops significantly improves when lightpaths can be dropped at the intermediate nodes or extended. In fact, at high loads, the LPwDwE algorithm was found to perform about 30 percent better in terms of the average number of logical hops when compared to the LPnDnE algorithm. Recall that lowering the average number of logical hops on an optical path results in less electronic processing. Fig. 10 also indicates that at low loads, LPwDnE performs better than LPnDwE, however, as the network load increases LPnDwE starts outperforming LPwDnE. This can be explained by the fact that under low loading condition, lightpaths have greater opportunities to be dropped. Simulation results show that similar trends can be observed when other grooming policies are implemented.

Figs. 11-12 show the performance of the LPwDwE algorithm using different grooming policies in terms of request blocking probability and average number of logical hops. Note that the best performance is achieved under the MTH grooming policy, whereas the MNL policy results in the poorest performance. Using the MNL policy, the LPwDwE algorithm attempts to use available resources prior to utilizing new ones. Thus, a few existing lightpaths can continue extending throughout the network, which in turn can potentially block more intermediate nodes from directly utilizing the wavelength channel. On the other hand, the MLH policy is expected to provide the lowest average number of logical hops. This is because, under such a policy, the LPwDwE algorithm attempts to satisfy connection requests using lightpaths passing through the least number of nodes.

Next, we examine the performance of LPwDwE using MTH grooming policy as the number receivers per node changes between 4 and 12. In this case, we assume the number of transmitters is fixed and set to 4. The results shown in Figs. 13-14 indicate that using the LPwDwE algorithm, as the number of receivers per node increases, the blocking probability and average number of logical hops improve. Such improvements become less apparent as the number of receivers continue to increase beyond $r = 10$. In fact, hardly any improvement is achieved as the number of receivers changes from 10 to 12. Similar trends can be observed under other grooming policies. Figs. 15-16 show the request blocking probability and average number of logical hops, respectively, using the LPnDnE algorithm as the number of receivers varies between 4 and 12. Note that the main performance improvement occurs when the number of receivers increases from 4 to 6. Additional receivers appear to have no major contribution to the performance. These results imply, that in general, compared to LPnDnE, the LPwDwE algorithm is more sensitive to the number of receivers per node, and it utilizes the receiver units more efficiently.

When lightpath extension is allowed, a few lightpaths can potentially *extend* and pass-through many nodes. This potentially results in blocking many intermediate nodes from directly accessing the wavelength channel. One way to minimize such cases is to impose a *hop constraint* in terms of number of nodes which can lie on a lightpath(s) connecting a node pair. Figs. 17-18 show the blocking probability and average number of logical hops using the LPwDwE and LPnDnE algorithms when a hop constraint is imposed. Due to lack of space, we only show the results for the MTH grooming policy. We choose the hop constraint to be twice the network diameter, $(2 \cdot 3 = 6)$. For moderate to high load conditions, imposing a hop constraint can improve the performance by about 6 percent. Fig. 17 suggests that under MTH, when the load is low, the hop constraint does not impact the blocking probability using the LPwDwE algorithm. This is because, under such conditions, lightpaths are less likely to be extended.

5 Conclusion

This paper addresses the problem of dynamic traffic grooming in WDM mesh networks under both uniform and non-uniform unicast traffic scenarios. In this study, we propose two effective traffic grooming concepts, namely, lightpath dropping and lightpath extension. These concepts are based on an alternative node architecture called drop-and-continue. In this architecture, incoming lightpaths can be dropped and switched electronically, while traversing to the next node optically. Based on these concepts, we develop several grooming algorithms. We investigate the performance of each algorithm in terms of request blocking probability and average number of logical hops under different network objectives. Comparing these results with the ones obtained from previously proposed lightpath-based grooming algorithms, it suggests that our proposed algorithms significantly improve the network performance when the number of transmitters is limited. We believe this preliminary work with careful power considerations can be extended to multicast traffic grooming in order to improve the network performance.

References

[1] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: a novel approach to high bandwidth optical WDN's," *IEEE Transactions on Communications,* vol. 40, no. 7, pp. 1171-1182, July 1992.

[2] A.L. Chiu and E.H. Modiano, "Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks," *IEEE/OSA Journal of Lightwave Technology,* vol. 18, no. 1 , pp. 2 -12, Jan. 2000.

[3] C. Xin, *et al.*, "An agent based traffic grooming and management mechanism for IP over optical networks," *Proceedings, IEEE ICCN 2002, Computer Communications and Networks,* pp. 425-430, Miami, FL, Oct. 2002.

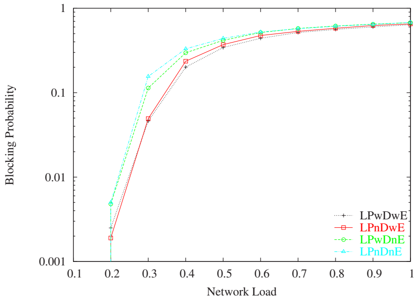


Figure 6: Blocking probability of different grooming algorithms using the MPH grooming policy.

[4] D. Zhemin, M. Hamdi, and J.Y.B Lee, "Integrated routing and grooming in GMPLS-based optical networks," *Proceedings, IEEE International Conference on Communications (ICC) 2004,* vol. 3, pp. 1584 - 1588, Paris, France, June 2004.

[5] R. Dutta and G.N. Rouskas, "Traffic grooming in WDM networks: past and future," *IEEE Network,* vol. 16, no. 6, pp. 46 -56, Nov.-Dec. 2002.

[6] O. Gerstel, P. Lin, and G. Sasaki, "Combined WDM and SONET network design," *Proceedings, IEEE INFOCOM 1999*, vol. 2, pp. 734-743, New York, NY, March 1999.

[7] V. R. Konda and T. Y. Chow, "Algorithm for traffic grooming in optical networks to minimize the number of transceivers," *IEEE Workshop on High Performance Switching and Routing (HPSR) 2001,* pp. 218-221, Dallas, TX, May 2001.

[8] A. R. B. Billah, B. Wang, and A. A. S. Awwal, "Effective traffic grooming algorithms for SONET/WDM ring net-works," *Photonic Network Communications*, vol. 6, no. 2, pp. 119-138, Sep. 2003.

[9] K. Zhu and B. Mukherjee, "Traffic grooming in an optical WDM mesh network," *IEEE Journal on Selected Areas in Communications,* vol. 20, no. 1, pp. 122-133, Jan. 2002.

[10] S. De Maesschalck, *et al.*, "Multi-layer traffic grooming in networks with an IP/MPLS layer on top of a meshed optical layer," *Proceedings, IEEE GLOBECOM 2003,* vol. 5, pp. 2750-2754, San Francisco, CA, Dec. 2003.

[11] H. Zhu, *et al.*, "Dynamic traffic grooming in WDM mesh networks using a novel graph model," *IEEE GLOBECOM 2002,* vol. 3, pp. 2681-2685, Taipei, Taiwan, Nov. 2002.

[12] K. Zhu and B. Mukherjee, "On-line approaches for provisioning connections of different bandwidth granularities in WDM mesh networks," *Proceedings, Optical Fiber Communication Conference and Exhibit (OFC)* 2002, pp. 549-551, Anaheim, CA, March 2002.

[13] C. Xin, C. Qiao, and S. Dixit, "Traffic grooming in mesh WDM optical networks - performance analysis," *IEEE GLOBECOM 2003,* vol. 7, pp. 3732-3736, San Francisco, CA, Dec. 2003.

[14] O. Gerstel, R. Ramaswami, and G.H. Sasaki, "Cost-effective traffic grooming in WDM rings," *IEEE/ACM Transactions on Networking,* vol. 8, no. 5, pp. 618-630, Oct. 2000.

[15] G. Huiban, S. Perennes, and M. Syska, "Traffic grooming in WDM networks with multi-layer switches," *Proceedings, IEEE International Conference on Communications (ICC) 2002,* vol. 5, pp. 2896-2901, Anchorage, AK, May 2002.

[16] M. Ali and J. Deogun, "Power-efficient design of multicast wavelength-routed networks," *IEEE Journal on Selected Areas in Communications,* vol. 18, no. 10, pp. 1852-1862, Oct. 2000.

[17] P.J. Lin and E. Modiano, "Traffic grooming in WDM networks," *IEEE Communications Magazine,* vol. 39, no. 7, pp. 124 -129, July 2001.

[18] C. Xin, C. Qiao, and S. Dixit, "Analysis of single-hop traffic grooming in mesh WDM optical networks," *Proceedings, SPIE OptiComm* 2003, pp. 91-101, Dallas, TX, Oct. 2003.

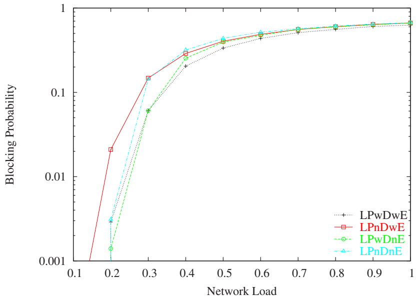


Figure 7: Blocking probability of different grooming algorithms using the MLH grooming policy.

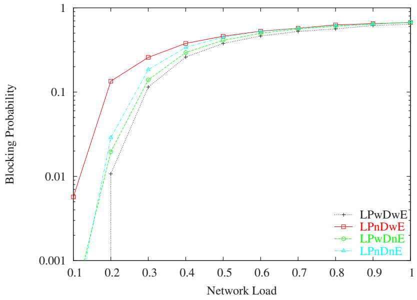


Figure 8: Blocking probability of different grooming algorithms using the MNL grooming policy.

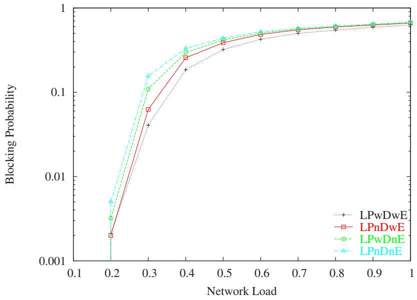


Figure 9: Blocking probability of different grooming algorithms using the MTH grooming policy.

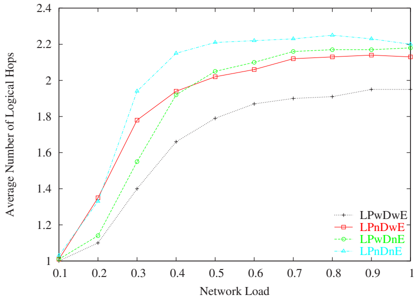


Figure 10: Average number of logical hops under different grooming algorithms using the MTH policy.

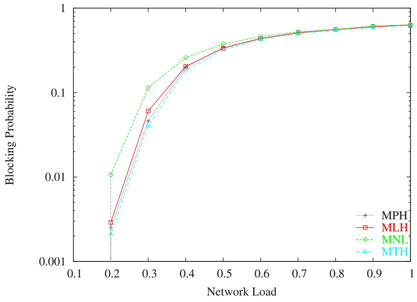


Figure 11: Blocking probability under LPwDwE using different grooming policies.

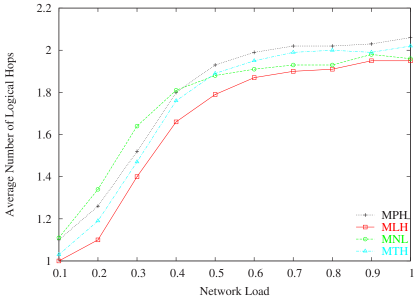


Figure 12: Average number of logical hops under LPwDwE using different grooming policies.

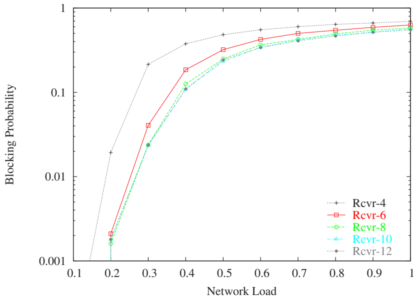


Figure 13: Blocking probability of LPwDwE using the MTH grooming policy with $t = 4$ and $r = [4, 6, 8, 10, 12]$.

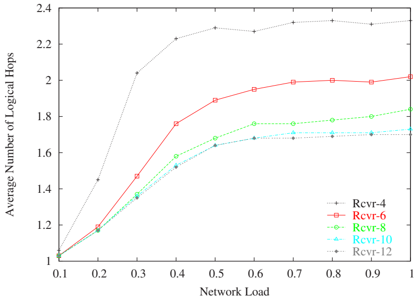


Figure 14: Average number of logical hops under LPwDwE using the MTH grooming policy with $t = 4$ and $r = [4, 6, 8, 10, 12]$.

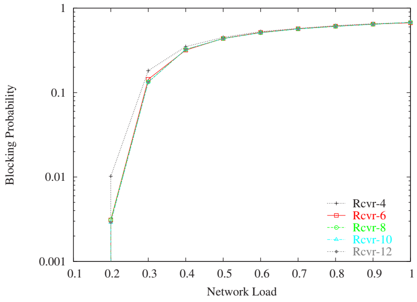


Figure 15: Blocking probability of LPnDnE using the MTH grooming policy with $t = 4$ and $r = [4, 6, 8, 10, 12]$.

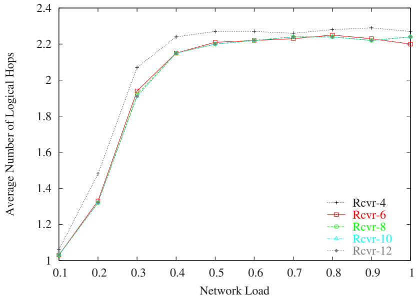


Figure 16: Average number of logical hops under LPnDnE using the MTH grooming policy with $t = 4$ and $r = [4, 6, 8, 10, 12]$.

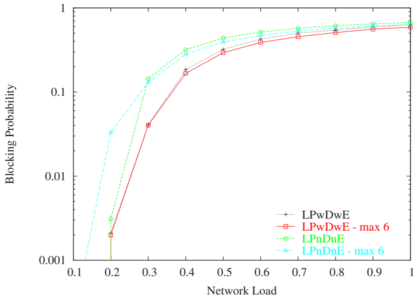


Figure 17: Blocking probability with a hop constraint of 6 using MTH grooming policy.

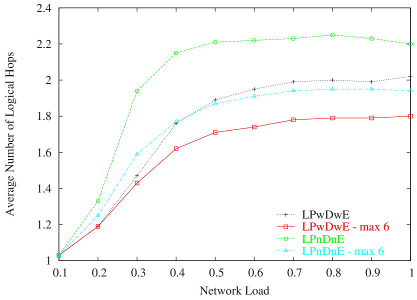


Figure 18: Average number of logical hops with a hop constraint of 6 using MTH grooming policy.