A Comprehensive Study on Next-Generation Optical Grooming Switches

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Abstract

This paper investigates performance of different optical grooming switches, i.e., optical grooming cross-connects (OXCs), under a dynamic traffic environment. Four optical grooming OXC architectures are presented, namely, single-hop grooming OXC, multi-hop partial-grooming OXC, multi-hop full-grooming OXC and lighttree-based source-grooming OXC. After exploring these OXCs' grooming capabilities, we proposed three grooming schemes and two corresponding algorithms, Grooming Using an Auxiliary Graph (GUAG) and Grooming Using Lighttree (GUL). Through these two algorithms, we evaluate the performance of different optical grooming OXCs in a dynamic traffic environment under different connection bandwidth-granularity distributions. Our experiment results illustrate that, (1) the multi-hop full-grooming OXC always has the best network performance, while it may encounter with cost and scalability constraints; (2) by using significantly less low-granularity electronic processing and through intelligent traffic-grooming algorithms, multi-hop partial grooming OXCs show reasonable good network performance; (3) the performance of a single-hop grooming OXC can be significantly improved by employing lighttree-based source-grooming scheme. From our results, we also observe that connection bandwidth-granularity distribution has a strong impact on network throughput and network resource efficiency, and hence should be carefully considered for network design and traffic provisioning.

I. Background Introduction

A. Next-Generation Optical WDM Networks

Fiber optics and wavelength-division multiplexing (WDM) technology have significantly increased the transmission capacity of today's transport networks, and played an extremely important role to support the explosively increased Internet traffic as well as large amount of traditional traffic. Using WDM technology, the bandwidth of a fiber link can be divided into tens (or hundreds) of non-overlapped wavelength channels (i.e., frequency channels), each of which can operate at the peek electronic processing rate, i.e., over gigabits per second. The bandwidth of a wavelength channel can be further divided into finer granularity trunk using Time-division multiplexing (TDM) technique and be shared by different end users. An end user can be any type of client network equipments such as IP, ATM or Frame relay network equipment. Hence, optical WDM network have served as an important platform (a circuit core) to provide network connectivity as well as transmission capacity to today's Internet infrastructure and application service.

As WDM switching technology keep maturing, optical WDM networks is expected to evolve from interconnected SONET/WDM ring topologies to irregular mesh topologies, and network provision procedure will migrate from an on-site manually interconnecting process to a point-and-click or on-demand automatic switching and connecting process. Such an intelligent optical WDM network is emerging under the jointly effort of optical switch development, optical network control plane standardization, and extensive optical WDM network research and experiment activity in industry and academic. Among different optical WDM switching technologies (i.e., circuit switching, burst switching, and packet switching), WDM circuit switching is known to be one of the most practical approaches to enable the next-generation optical network. Hence, this study concentrates on an intelligent optical circuit-switched WDM transport (backbone/metro) network.

B. Traffic Grooming in Next-Generation Optical WDM Networks

Traffic grooming is a procedure of efficiently multiplexing/demultiplexing and switching low-speed traffic streams onto/from high-capacity bandwidth trunk in order to improve bandwidth utilization, optimize network throughput and minimize network cost. Though the grooming concept has existed in telecommunication industry for years (e.g., S0 to T1, T1 to SONET STS-1), because of the lack of intelligent network control and automatic provisioning functionality, traditional traffic-grooming is more like a multiplexing/demultiplexing concept rather than an efficient hierarchical multi-granularity switching and end-to-end provisioning concept. Traffic grooming is an extremely important issue for next-generation optical WDM networks to efficiently perform end-to-end automatic provisioning. In different sophistical WDM networks domains, different multiplexing technologies may be applied for traffic grooming. For example, TDM scheme can be used to perform time-slot to wavelength channel grooming in a SONET/SDH over optical WDM network environment; WDM scheme can be used to perform wavelength channel to waveband grooming or wavelength/waveband to fiber grooming in an all-optical WDM network environment[1]; and statistical-based packet-division multiplexing (PDM) scheme can be used to perform packet flow or virtual circuit (VC) to wavelength channel grooming in a IP over WDM network environment, etc. Different multiplexing techniques may impose different grooming constraints in optical networks. In this study, we consider a hybrid TDM-over-WDM (SONET/WDM) based optical network environment, in which optical crossconnects (OXCs)[2] of different switching architectures are used to constructed a intelligent next-generation optical core network.

C. Related Study and Our Contribution

Most of earlier traffic-grooming research focused on network design optimization of SONET/WDM ring networks [3]-[10]. By employing wavelength add-drop multiplexer (W-ADM) and through proper wavelength

[1] An all-optical WDM network can switch traffic at optical domain, without converting optical signals to electronic signals.

[2] Note that, OXC is known as another name for an intelligent optical switch, we use these two terminologies interchangeable in this paper.

assignment and SONET time-slot assignment algorithms, network operators can design their SONET/WDM network to accommodate all traffic requests, and at the same times minimize network cost which is dominated by the number of SONET electrical add-drop multiplexers (ADMs).

In recent years, as optical transport networks keep evolving from interconnected SONET/WDM ring networks to irregular mesh-based optical WDM networks, increasing amount of research efforts have been conducted on traffic-grooming problem in optical WDM mesh networks. The authors in [11] study the traffic provisioning optimization problem with grooming consideration. Two mesh grooming node architectures are presented. The problem is formulated as an integer linear program (ILP), and two heuristic algorithms are proposed as well. The authors in [12] quantitively compare the network cost gain by employing grooming capability at optical core networks. By using the OXCs of different grooming and switching characteristic in a 46-node optical core network, the authors evaluated the network cost performance for a given static traffic demand. A generic graph model is presented for provisioning connections in a multi-granularity multi-wavelength optical WDM network in [13]. The authors show that different network optimization objectives and corresponding route selection schemes can be easily accommodated by this graph model. Based on this model, the authors propose several grooming heuristics for given static traffic demand and show that these heuristics can achieve near-optimal solution. The work in [15]-[18] considered traffic-grooming issues in dynamic traffic environment. The authors in [15] observed that in a multi-granularity WDM network, it is more possible to block the connections with high bandwidth requirement than to block those with low bandwidth requirement, which results in unfairness between connections of different bandwidth-granularity classes. Hence, they propose a call admission control (CRC) algorithm to achieve the fairness. The authors in [16] and [17] study the on-line provisioning mechanisms for connections of different bandwidth granularities in traffic-groomable WDM network. Several algorithms are proposed to optimize overall network performance. The authors in [18] proposed a generalized network model called trunk switched network (TSN) to facilitate the modeling and analysis of a multi-wavelength TDM switched networks. They analyze the blocking performance of TSN and extended their model to analyze the blocking performance of multicast tree establishment in optical WDM networks.

In this study, we systematically investigate and evaluate the characteristics of different optical grooming switches, i.e., the optical crossconnects (OXCs) with traffic-grooming capability. According to various OXC architectures, we explore and propose different possible traffic-grooming schemes, and compare the performance of those schemes under a dynamic traffic environment. To the best of our knowledge, this is one of the first work which comprehensively examines the characteristics and performance of different types of optical grooming OXCs for dynamic traffic under different connection bandwidth-granularity distributions. Our investigation will help network operators to cost-effectively design and operate a optical groomable WDM backbone network, and it will be also helpful for system vendors to develop high-performance grooming OXCs.

D. Organization

The rest of the paper is organized as follows: In Section II, we introduce different optical grooming OXCs and explore their corresponding grooming schemes. Furthermore, Section III presents the detail approaches and algorithms for the proposed grooming schemes using different grooming OXCs. The experimental and numerical results are shown and analyzed in Section IV. Section V concludes the study.

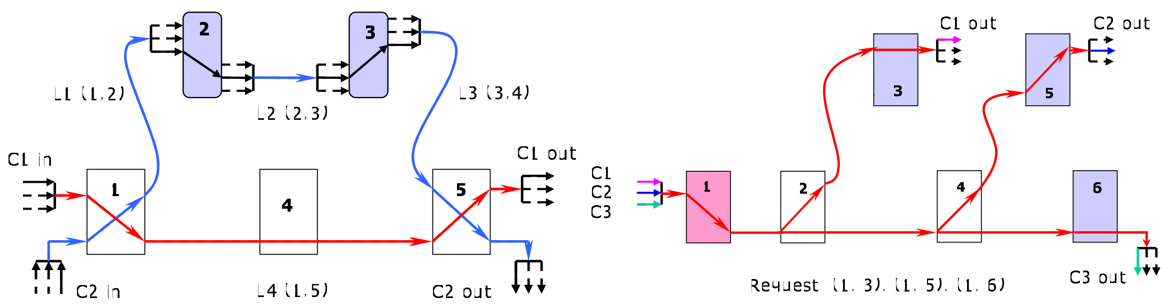
II. Different Grooming Switch Architectures and Corresponding Grooming Schemes

In an optical WDM network, the lightpath [1][2], provides a basic communication mechanism between two network nodes. From traffic-grooming perspective, a lightpath is a circuit with full wavelength capacity. It may span one or multiple fiber links and be routed by intermediate switching nodes. Low-speed traffic streams will be packed to a lightpath at its end nodes by grooming OXCs. There are transparent (all-optical) or opaque switching technologies to implement those OXCs. Transparent (all-optical) technology refers to the switching without optical to electronic (OE) conversion. Opaque technology refers to the switching with OE conversion. Different technologies and architectures may lead to different grooming OXCs, which may be capable for different grooming schemes. Specifically, there are three different grooming schemes, namely *single-hop grooming, multi-hop grooming, and source-node grooming*. Each type of grooming OXCs may support one or multiple grooming schemes. Those grooming OXCs with their corresponding grooming schemes can be categorized as follows.

A. Single-hop grooming OXC

An OXC can be called a single-hop grooming OXC if (a) it can only switch as wavelength granularity, and (b) it has low-date-rate interfaces (ports) which can be used to directly support low-speed traffic streams from client network equipment. Note that, co-operated with a separated network aggregation equipment (e.g., an electrical multiplexer), an OXC with only wavelength ports and only switching at wavelength granularity can also be viewed as a single-hop grooming OXC. Using this OXC, low-speed traffic from clients can be multiplexed onto a wavelength channel using a TDM scheme. Since this OXC does not have the capability to switch low-speed streams, the low-speed streams on one wavelength channel from a source node will be switched to the same destination node, i.e., a low-speed connection can only traverse a single lightpath hop. Thus, this end-to-end grooming scheme is called single-hop grooming scheme.

Figure 1(a) shows how a low-speed connection ($C1$) is carried by a lightpath ($L4$) from node 1 to node 5. Note that, in Fig. 1(a), the node 1, 4, and 5 are equipped with single-hop grooming OXCs, which can only switch at wavelength channel granularity.



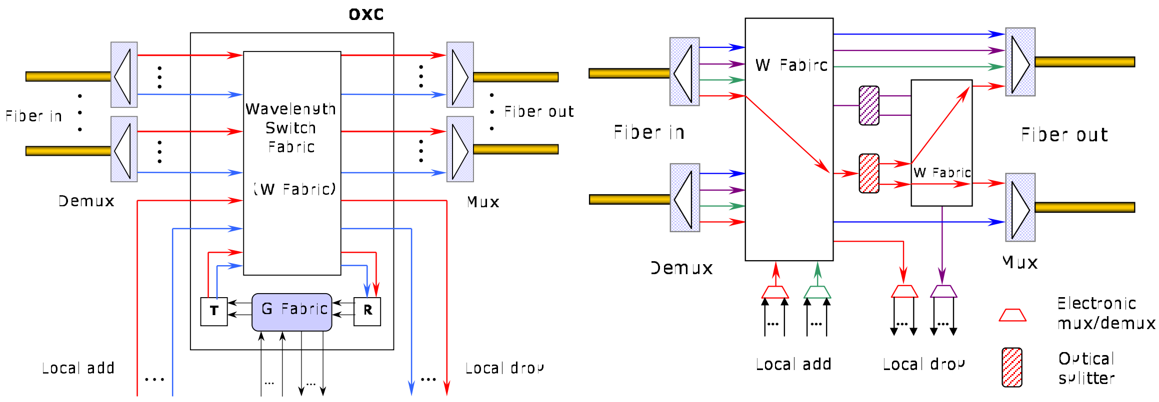
(a) (b)

Fig. 1. Exmaples of single-hop, multi-hop, and source-node grooming schemes.

B. Multi-hop partial-grooming OXC

A multi-hop partial-grooming OXC consists of two switch fabrics, a wavelength-switch fabric (W-Fabric) which can be either all-optical or electronic, and an electronic-switch fabric which can switch low-speed traffic streams. The electronic-switch fabric is also called grooming fabric (G-Fabric). With this hierarchical switching and multiplexing architecture, this OXC can switch low-granularity traffic stream from one wavelength channel to other wavelength channels and groom them with other low-speed streams without using any extra network element. Assuming that the wavelength capacity is OC-N and the lowest input port of the electronic switch fabric is OC-M ($N \geq M$), the ratio between N and M is called the "grooming ratio". In this architecture, only a few of wavelength channels (lightpaths) can be switched to G-fabric and perform switching at finer granularity level. The number of ports, which connect the wavelength switch fabric and G-fabric, determines how much multi-hop grooming capability this OXC has. Figure 2(a) shows a simplified multi-hop partial-grooming OXC architecture. A multi-hop partial-grooming OXC can support both single-hop grooming and multi-hop grooming schemes.

Figure 1(a) shows how a low-speed connection ($C1$) is carried by multiple lightpaths ($L1$, $L2$, and $L3$) from node 1 to node 5. Note that, node 2 and node 3 are equipped with multi-hop partial-grooming OXCs,



(a) (b)

Fig. 2. Sample grooming OXC architectures: a multi-hop partial-grooming OXC and a source-node grooming OXC.

and only the G-fabrics are shown in the figure.

Figure 1(a) also shows that there may exist four types of lightpath in a WDM network which employs multi-hop partial-grooming OXCs. Now, assuming all network nodes are equipped with multi-hop partial-grooming OXCs, and only the G-fabrics of node 2 and 3 and W-fabrics of node 1, 4, and 5 are shown in the figure. The lightpath $L1$, $L2$, $L3$, and $L4$ represent these four lightpath types.

- *Multi-hop ungroomable lightpath* ($L4$): A lightpath (i, j) is a multi-hop ungroomable lightpath if it is not connected with finer granularity switching element at its end nodes. This lightpath can only be used to carry the traffic directly between node pair (i, j). Lightpath $L4$ in Fig. 1(a) is a multi-hop ungroomable lightpath.
- *Source-groomable lightpath* ($L3$): A lightpath (i, j) is a source-groomable lightpath if it is only connected with finer granularity switching element at its source node. All traffic on this lightpath has to terminate at node j, but the traffic may originate from any other network node. Lightpath $L3$ in Fig. 1(a) is a source groomable lightpath.
- *Destination-groomable lightpath* ($L1$): A lightpath (i, j) is a destination-groomable lightpath if it is only connected with finer granularity switching element at its destination node. All traffic on this lightpath has to originate from node i. At the lightpath destination node j, the traffic on lightpath (i, j) can either terminate at j or be groomed to other lightpath and route toward other nodes. Lightpath $L1$ in Fig. 1(a) is a destination-groomable lightpath.
- *Full-groomable lightpath* ($L2$): A lightpath (i, j) is a full groomable lightpath if it connects to finer granularity switching element at both end nodes. This lightpath can be used to carry traffic between any node pair in the network. Lightpath $L2$ in Fig. 1(a) is a full-groomable lightpath.

In a optical WDM network employing multi-hop partial-grooming OXCs, those lightpaths can either be established dynamically according to current connection requests, or be preplanned based on forecasting traffic demands.

C. Multi-hop full-grooming OXC

A multi-hop full-grooming OXC can provide full-grooming functionality, i.e., every OC-N wavelength channel will be demultiplexed into multiple OC-M streams before it enters the switch fabric. The switch fabric can switch these OC-M traffic streams in a non-blocking manner. The switched streams will be multiplexed back to different wavelength channels. An OXC with full-grooming functionality has to be built using the opaque approach.

When a WDM network employs multi-hop full-grooming OXC at every network node, each wavelength channel at every fiber link connected by two network nodes forms a full-groomable lightpath. In this way, the virtual topology (i.e., lightpath topology) are exactly the same as the physical topology (fiber topology), and a traffic stream can be easily switched from one time-slot of a wavelength channel to another time-slot of a wavelength channel (can be the same or different channel). at every intermediate node it traverses. A multi-hop full-grooming OXC can support single-hop or multi-hop grooming scheme.

D. Lighttree-based source-node grooming OXC

Optical “lighttree’ has been proposed to support multicast applications in optical WDM networks [19]-[20]. A lighttree is a wavelength tree which connects one source node and multiple destination nodes. Through a lighttree, The traffic from the source node will be delivered to all destination nodes of the tree. Establishing lighttree in an optical WDM network requires that network nodes have multicast capability. In order to support multicasting, an OXC need duplicate the traffic from one input port to multiple output ports. For an OXC using transparent technology, this duplication can be done in optical domain using an optical splitter by splitting the power of optical signals from one input port to multiple output port. For an OXC using opaque technology, the traffic duplication can be easily accomplished by copying electronic bit stream from one input port to multiple output ports. Figure 2(b) shows a simplified architecture of a multicast-capable OXC using the transparent technology.

Figure 1(b) shows how to use OXCs’ multicast capability to perform traffic grooming. There are three low-speed traffic steams from the same source node 1 to different destination nodes 3, 5, and 6. By setting up a lighttree, these three traffic streams can be packed to the same wavelength channels, and delivered to all destination nodes (i.e., lighttree leaf node). At each destination node, only the needed traffic streams is

Type \ Charac.	Grooming capability	Provisioning flexibility	Switching capacity	Cost	Scalability	Optical bypassing	Technology maturity
Single-hop grooming OXC	poor	poor	largest	low	good	can	medium/medium
Source-node grooming OXC	good	good	largest	meduim	good	can	medium/low
Multi-hop partial-grooming OXC	better	better	large	medium	good	can	medium/low
Multi-hop full-grooming OXC	best	best	small	high	poor	cannot	high/high

TABLE I

A SUMMERY OF THE CHARACTERISTICS OF DIFFERENT OPTICAL GROOMING SWITCHES

picked up and relayed to client equipments. In this way, the low-speed traffic from the same source node can be groomed to the same wavelength channel and be sent to different destination nodes. Please note that, if a connection between a node pair requires full wavelength-channel capacity, a lighttree becomes a lightpath. We call this grooming scheme lighttree-based source-node grooming scheme. From traffic-grooming perspective, the multicast-capable OXC can be called lighttree-based source-node grooming OXC. Such an OXC can support lighttree-based source-node grooming scheme as well as single-hop grooming scheme.

E. Overview of different grooming schemes and grooming switch architectures

As an overview, we can see that, single-hop grooming scheme can only groom traffic from the same source node to the same destination node; lighttree-based source-node grooming scheme can groom traffic from the same source node to different destination nodes, and multi-hop grooming schemes may groom traffic from different source nodes and to different destination nodes.

Table I summarizes the characteristics of different optical grooming switches (OXCs). The multi-hop full-grooming OXC has the best grooming capability and provisioning flexibility. It can only be implemented using the opaque technology. Hence, it requires significantly amount of electronic processing, which potentially leads to its poor scalability and high cost (normalized per bit switching cost). Since it has build-in wavelength conversion capability and full-grooming capability, the network control of this OXC encounters less physical constraints and will be relatively easy to be developed.

The single-hop grooming OXC, on the other hand, has poor grooming capability and does not have too much flexibility to provision connections of different bandwidth granularity, since only the single-hop grooming scheme is supported. Both transparent (less mature) and opaque technology (more mature) can be used to develop the OXC. As the OXC switches traffic at high granularity level, it can have the largest switching capacity and the lowest cost (normalized per bit switching cost). The single-hop grooming OXC with transparent technology also has good scalability (for wavelength-band switching, fiber switching). Depending on the implementation, the OXC may employ wavelength-continuity constraint, if it is built using transparent technology and it has no wavelength-conversion capability or only has partial wavelength-conversion capability. Hence, certain intelligent control software support are needed. Provisioning connections in a WDM network with wavelength-continuity constraint is known as a standard routing and wavelength assignment (RWA) problem and has been well addressed in the literature.

Most characteristics of the source-node grooming OXC and the multi-hop partial grooming OXC are between those of the single-hop grooming OXC and the multi-hop full-grooming OXC. Intelligent algorithms are needed for WDM networks which employ lighttree-based source-node grooming OXCs (or multi-hop partial-grooming OXCs) to efficiently setting up lighttree (or multi-hop groomable lightpath). Comparing with RWA problem, there are relatively less references in the literature, and more efforts are needed on the development of these algorithms to perform efficiently traffic grooming and to optimize network resource utilization.

III. Approaches and Algorithms

In this section, we present two approaches and algorithms to efficiently achieve the propsed grooming scheme in a optical WDM network, one for single-hop and multi-hop grooming schemes and the other for lighttree-based source-node grooming scheme.

A. Single-hop and multi-hop grooming using an auxiliary graph model

1) Grooming Policies and an Auxiliary Graph Model: In a traffic-groomable WDM network, there may be multiple ways to carry a low-speed connection request, i.e., there may exist multiple routes from a given source node to a given destination node, each of which may use different amount of network resources, e.g., wavelength channels, grooming capability, etc. The decision of how to choose a proper route from multiple candidates is known as the "grooming policy". Different grooming policies reflect the network operators' intention on how to engineer their network traffic using available network resources. For example, a low-speed connection can be carried through existing lightpaths, or by setting new lightpath between given node pair. The effect of different grooming polices on traffic grooming problem has been addressed in [13], [17].

We extend a generic graph model, which was originally proposed in [13], to handle the single-hop grooming and the multi-hop grooming schemes. The extended model can uniformly incorporate different grooming OXC architecture (single-hop grooming OXC, multi-hop partial-grooming OXC and multi-hop full-grooming OXC) and easily achieve different grooming policies. In this model, an auxiliary graph is constructed for a given network state. The route of a connection request is computed based on the auxiliary graph. We use $G(V, E)$ to denote a given network state, where V denotes the network node set (i.e., the OXCs) and E denotes the network link set, (i.e., the fiber links and the lightpath links). We then use $G(V', E')$ to denote the corresponding auxiliary graph, where V' denotes the vertex set and E' denotes the edge set. From now on, for clarity, we will use the terms *node* and *link* to represent a vertex and an edge in the original network state $G(V, E)$, respectively, and we will use the terms *vertex* and *edge* to represent a vertex and an edge in the auxiliary graph $G'(V', E')$, respectively.

The auxiliary graph $G'(V', E')$ can be divided into four layer, namely access layer, mux layer, grooming layer and wavelength layer. The access layer represents the access point of a connection request, i.e., the point where a customer's connection starts and terminates. It can be an IP router, an ATM switch, or any other client equipment. The mux layer represents the ports from which low-speed traffic streams are directly multiplexed (demultiplexed) onto (from) wavelength channels and switched by W-Fabric without going through any G-Fabric. It can be an electronic multiplexer/demultiplexer, a SONET ADM, etc. The grooming layer represents the grooming (i.e., mux/demux and switching low-speed traffic streams) component of the network node, e.g., grooming fabric. The wavelength layer represents the wavelength-switching capability. A network node is divided into two vertices at each layer. These two vertices represent the input port and output port of the network node at that layer. Fig. 3 shows the graph representation of different grooming OXCs. For simplification reason, assume the every network node has full wavelength-conversion capability. The edges in Fig. 3 represent the resource availability at a given network node. It also denotes the reachability from a given port of a given layer to another port of another layer in a network node. A connection request between node pair (i, j) always originates from the output port of the access layer in node i and terminate at the input port of the access layer in node j. Note that, through some straightforward extensions (by stretching the single wavelength layer to multiple layers, one for each wavelength), the network without full wavelength-conversion capability can also be properly modeled.

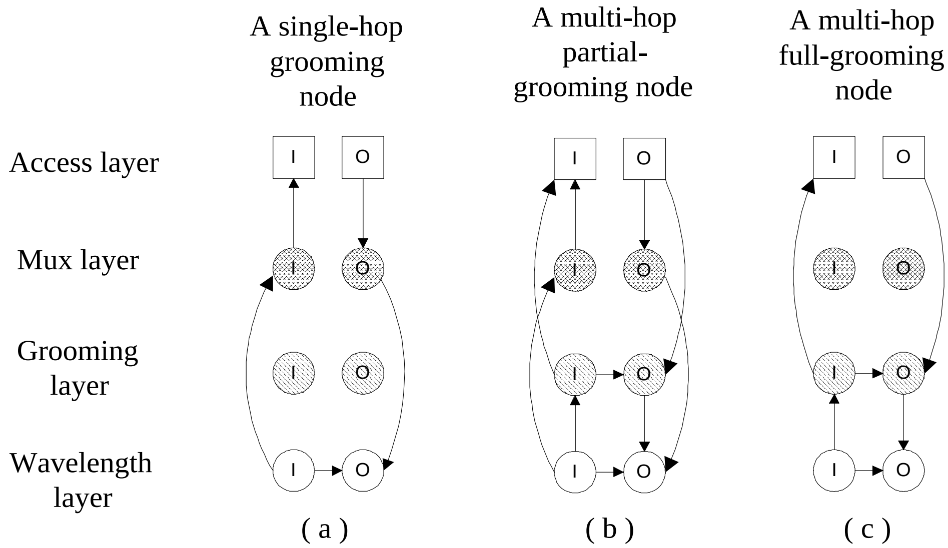


Fig. 3. Different grooming OXCs and their representations in the auxiliary graph.

The links in the original network state graph $G(V, E)$ can be represented by the edges which connected the vertices from one network node to another network node shown in Fig. 3. We explain them as follows.

- A *wavelength link* (i, j) can be represented by an edge which connects the output port of the wavelength layer in node i to the input port of the wavelength layer in node j.
- A *multi-hop ungroomable lightpath* (i, j) can be represented by an edge which connects the output port of the mux layer in node i to the input port of the mux layer in node j.
- A *source-groomable lightpath* (i, j) can be represented by an edge which connects the output port of the grooming layer in node i to the input port of the mux layer in node j.
- A *destination-groomable lightpath* (i, j) can be represented by an edge which connects the output port of the grooming layer in node i to the input port of the mux layer in node j.
- A *full-groomable lightpath* (i, j) can be represented by an edge which connects the output port of the grooming layer in node i to the input port of the grooming layer in node j.

Figure 4 illustrates how to construct the auxiliary graph for a given network state. Figure 4(a) and 4(b) show the network state for a simple 3-node network. The shaded node (node 0) is the node which employs a multi-hop partial-grooming OXC and the un-shaded nodes (node 1 and 2) are equipped with single-hop grooming OXCs. Each link in Fig 4(a) represents a free wavelength channel between a node pair and each link in Fig 4(b) represents an established lightpath. The lightpath $(0, 2)$ is a source-groomable lightpath, the

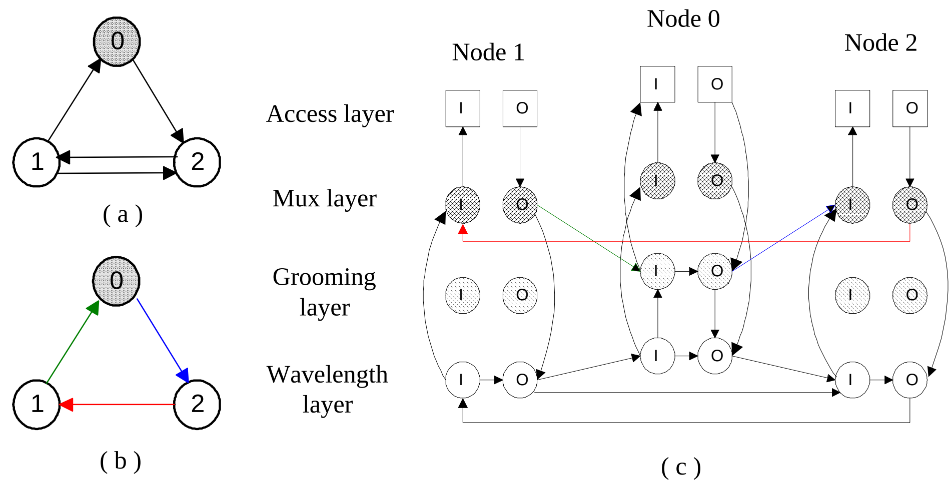


Fig. 4. Network state for a simple three-node network and the corresponding auxiliary graph.

lightpath $(1, 0)$ is a destination-groomable lightpath, and the lightpath $(2, 1)$ is a multi-hop non-groomable lightpath. A low-speed connection request from node 1 to node 2 can be carried by lightpaths $(1, 0)$ and $(0, 2)$. On the other hand, a request from node 2 to node 0 cannot traverse lightpaths $(2, 1)$ and $(1, 0)$ since node 1 do not have multi-hop grooming capability. According to the network state shown in Fig 4(a) and 4(b), we can construct the auxiliary graph, which is shown in 4(c).

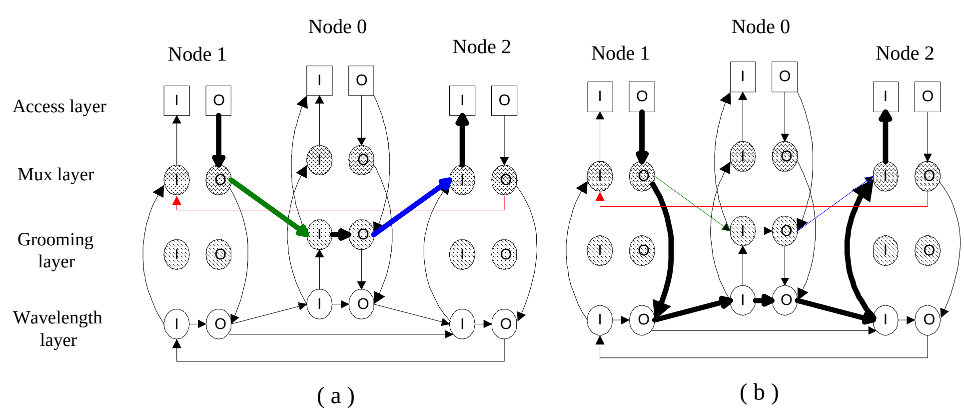


Fig. 5. Two alternative routes which can be found using the auxiliary graph.

2) Grooming using auxiliary graph (GUAG) algorithm: This auxiliary graph can be used to provision customers' connection requests. By assigning proper weight (i.e., administrative link cost) to each edge in the auxiliary graph, suitable routes will be computed through standard shortest-path computation algorithms according to different grooming policies. Figure 5 illustrates how to achieve different grooming policies by using this graph model. The network state and the auxiliary graph representation are shown in Fig 4. Suppose that there is a traffic request from node 1 to node 2, Fig. 5 shows two possible routes (in thick edges) for this connection request. The route shown in Fig. 5(a) traverses two existing lightpath links, while the route shown in Fig. 5(b) employs two new wavelength-link channels. If the connection requires full wavelength channel capacity, the route in Fig. 5(b) is preferred since wavelength channels are fully utilized and no grooming is needed at node 0; otherwise, the route in Fig. 5(a) may be preferred. More detailed study on how to use this graph model to achieve different grooming policies and how those grooming policies may affect network performance can be found in [13]. Based on the model, we design an algorithm, call Grooming Using Auxiliary Graph (GUAG), which can be used to provision connections of different bandwidth granularities. This algorithm can be used in a WDM network which employs single-hop grooming OXCs, multi-hop partial-grooming OXCs, or multi-hop full-grooming OXCs

3) Computational Complexity of GUAG: In GUAG, the time complexity to construct an auxiliary graph for a N node, full-wavelength-convertible WDM network, is $O(N^2)$, because the auxiliary graph of such a network will consist of $2 \times 4 \times N$ vertices and at most $(2 \times 4 \times N)^2$ edges. Consequently, the computational complexity of Step 1 and Step 2 is $O(N^2)$. Step 3 computes a least-cost route between two given vertices based on the auxiliary graph using standard shortest-path algorithm. Since the auxiliary graph has $2 \times 4 \times N$, the computational complexity of Step 3 is also $O(N^2)$. The computational complexity of the remaining steps of is $O(N)$. Therefore, the overall computational complexity of GUAG is $O(N^2)$ for a full-wavelength-convertible WDM network. Using the same analogy, we can see that the computational complexity of GUAG will be $O(N^2W^2)$ in a WDM network without full-wavelength conversion capability, where W is the number of wavelength channels supported by the network.

B. source-node grooming using lighttree approach

the auxiliary graph model and the GUAG algorithm cannot be used to handle source-node grooming scheme using lighttree approach. Hence, we design another algorithm to perform lighttree based source-grooming in a WDM network employing source-node grooming OXCs. Note that, in a WDM network using lighttree-based source-grooming scheme, the network state can be represented as a graph $G(V, E, T)$ where V denotes the network node set, E denotes the network link set, and T denotes the established lighttree set.

1) Grooming Using Lighttree (GUL) algorithm: The proposed algorithm for lighttree-based source-grooming scheme is described as follows.

2) Computation Complexity of GUL: In the Step 2 of GUL, the computational complexity to find the closest node i to the destination node d in a given lighttree T_s is $O(N^2)$. This is because that node i can be

Algorithm 1 Grooming Using auxiliary Graph (GUAG)

Input: Network state $G(V, E)$, and a connection request $Req(s, d, c)$ where s and d denote the source and destination node of the request (i.e. $s, d \in V$) , and c denotes the capacity requirement.

Output: A route R between node s and d, which satisfies the connection's capacity requirement and a new network state $G_{new}(V_{new}, E_{new})$ after provisioning the connection.

1) Construct the auxiliary graph $G'(V', E')$ according to network resource availability and the bandwidth requirement of the request, i.e., (a) If there is no free wavelength on a fiber connected a given node pair (i, j), there is no edge connects the vertices of wavelength layer between node pair (i, j); (b) If there is no lightpath link between node pair (i, j), or lightpaths between (i, j) do not have enough free capacity for Req, there is no corresponding edge in the auxiliary graph; (c) If a multi-hop partial-grooming OXC at a given node i has used up all grooming ports, there is no edge between the vertices of the grooming layer and the wavelength layer at node i.
2) Assign proper weight to each edge in G', according to the grooming policy. The grooming policy we used in this study is described as follows.
    a) If there is any multi-hop ungroomable lightpath between (s, d) with enough free capacity, carry Req using this lightpath.
    b) otherwise, a connection is provisioned through the least-cost route. In this study, the cost of a fiber link is assume to be unity. The cost of a lightpath link is equal to the overall cost of the concatenated fiber links it traverses.
    c) If there are multiple least-cost routes and the connection does not require full wavelength-channel capacity, select the route which employs the minimal number of free wavelength links.
    d) If there are multiple least-cost routes and the bandwidth requirement of the connection requires full wavelength-channel capacity, select the route which traverse the minimal numbers of electronic grooming fabrics.

    Please refer to [13] on how to assign proper edge weight to the auxiliary graph according to a grooming policy.
3) Compute a route R' based on the auxiliary graph G'. if fails, return null.
4) Map R' in G' to route R in original network state graph G.
5) Allocate resource and update the network state according to the route R. It may include the operations of (a) updating available wavelength number on fiber links along the route R, if it is necessary; (b) creating new lightpath links if it is necessary; (c) updating the grooming port number in a partial-grooming OXC R traverses if it is necessary, and (d) updating the free capacity of a lightpath involved in R, if it is necessary. Note that, if there is multiple applicable lightpaths between a node pair (i, j) along the route R, we will random choose one lightpath for Req.
6) Return R and the updated network state $G_{new}(V_{new}, E_{new})$

Algorithm 2 Grooming Using Lighttree (GUL)

Input: Network state $G(V, E, T)$, and a connection request $Req(s, d, c)$ where s and d denote the source and destination node of the request (i.e. $s, d \in V$) , and c denotes the capacity requirement.

Output: A lighttree T_s' which is rooted at node s and covers node d as a destination node, and a new network state and a new network state $G_{new}(V_{new}, E_{new}, T_{new})$ after provisioning the connection.

1) Let T_s denote a given established lighttree rooted at node s, if node d is one of leaf node of tree T_s and T_s have enough free capacity for Req, Let $T_s^{'}$ be equal to T_s, and go to Step 5. Note that, if multiple such tree exists, randomly pick one to be the T_s'.
2) For any given T_s which have enough free capacity to carried Req, compute a least-cost route from every node in T_s to node d, subject to available wavelength link constraint, and available splitter constraint at node i (if the transparent technology is used to build the OXC at node i, as shown in Fig. 2(b)). Let i denote the node which have the least-cost route to d among all the tree node. If no such tree exist, go to Step 4.
3) Find out the tree $T_s^{'}$ and the corresponding node i' such that node i' is the closest one to node d among all tree nodes of all candidate trees. If the node i' is the root node of $T_s^{'}$, go to Step 4, otherwise, extend the tree to include a new tree branch from node i' to node d. Thus, node i' need duplicate the traffic originating from node s and route it to node d. After that, go to step 5.
4) Set up a lighttree from node s to node d following the least-cost route based on current network state. Note that, this special lighttree instance only has one destination node. Hence, it is equivalent to a lightpath. Let this lighttree to be $T_s^{'}$.
5) Allocate free capacity of $T_s^{'}$ to Req. If $T_s^{'}$ is a new tree or if $T_s^{'}$ is a established tree but a new branch has been added to $T_s^{'}$, update the corresponding wavelength link availability information.
6) Return $T_s^{'}$ and the new network state $G_{new}(V_{new}, E_{new}, T_{new})$.

found by constructing a shortest-path tree T_d rooted at node d. In T_d, we can easily find the closest node (to node d) which is also in the tree T_s. That node will be the node i needed in Step 2. Assuming that there is K candidate lighttrees rooted at node s, which can be expended to support the connection request, the computational complexity for Step 2 and Step 3 will be $O(KN^2)$. The computational complexity of other steps in GUL is $O(N)$. Hence, the computational complexity of GUL is $O(KN^2)$

IV. Illustrative Numerical Results

We simulate a dynamic network environment to compare the performance of different optical grooming switches and their corresponding grooming schemes, using proposed algorithms, GUAG and GUL. We assume that every network node is equipped with same type of grooming OXCs. The connection arrival process is assumed to be Poisson and the connection holding time follows a negative exponential distribution. For the illustrative results shown here, the capacity of each wavelength is OC-192; the network has full wavelength-conversion capability and each fiber link can support eight wavelength channels; when multi-hop partial-grooming OXCs are used, it is assumed that each of them has six (incoming and outgoing) grooming ports; it is also assumed that the lighttree-based source-node grooming OXC considered is built using the opaque technology and hence has unlimited multi-cast capability; a connection request can have any bandwidth granularity of $OC-1$, $OC-3$, $OC-12$, $OC-48$ and $OC-192$; Three bandwidth-granularity distributions for the number of connection requests ($OC-1 : OC-3 : OC-12 : OC-48 : OC-192$) is examined, $3 : 3 : 3 : 3 : 1$, $1 : 1 : 1 : 1 : 1$, and $1 : 1 : 1 : 1 : 3$; connections are uniformly distributed among all node pairs; average connection holding time is normalized to unity; load (in Erlang) is defined as connection arrival rate times average holding time times a connection's average bandwidth and it is normalized to the unit of OC-192. The example network topology used in our experiment is shown in Fig. 6.

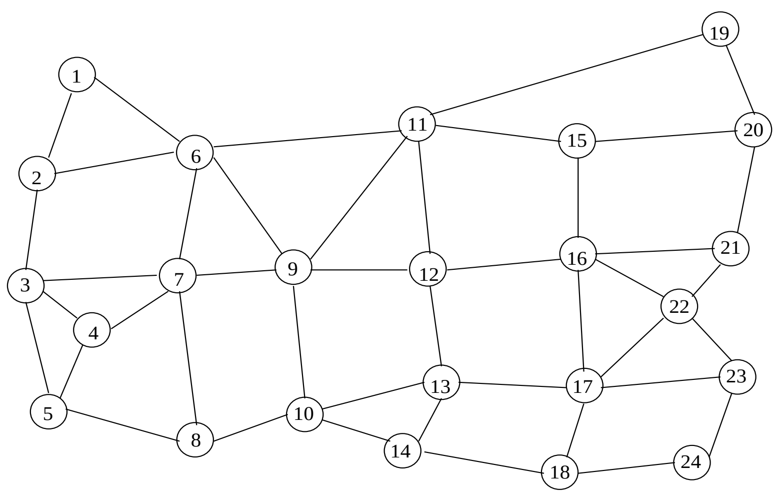
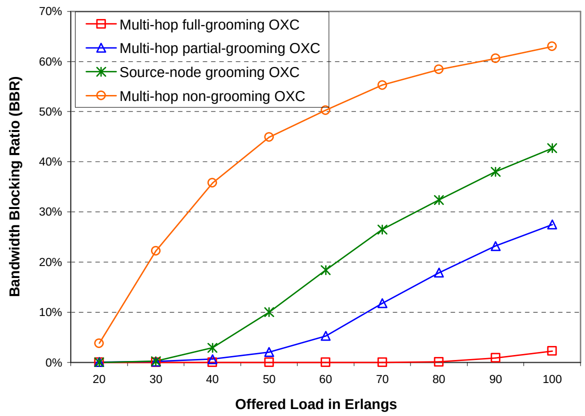


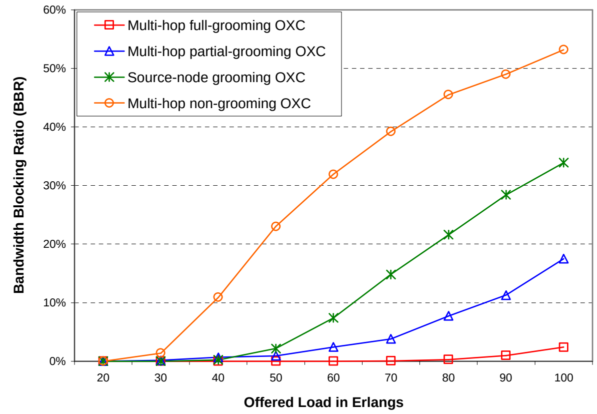
Fig. 6. A 24-node sample network topology.

A. Bandwidth Blocking Ratio (BBR)

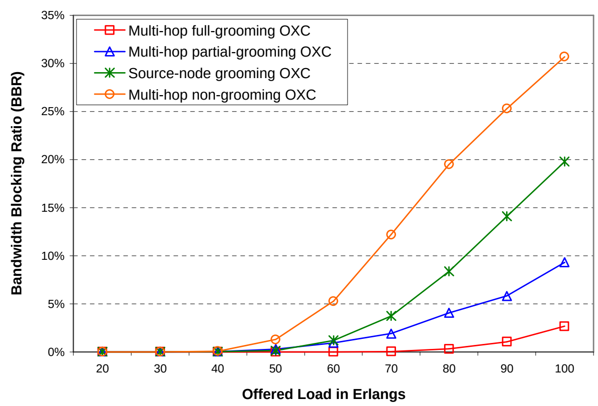
Figure 7 compares the network performance (bandwidth blocking ratio (BBR) vs. load) by using different optical grooming OXCs under different connection bandwidth-granularity distributions. BBR represents the percentage of the amount of blocked traffic over the amount of bandwidth requirement of all traffic requests during entire simulation period. Note that pure blocking probability cannot reflect the effectiveness of the algorithm as connections have different bandwidth requirements.



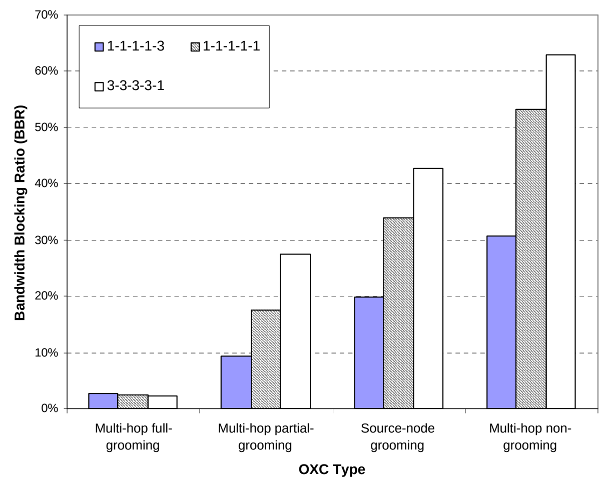
(a) $3:3:3:3:1$



(b) $1:1:1:1:1$



(c) $1:1:1:1:3$



(d) $Erlang = 100$

Fig. 7. Bandwidth blocking ratio (BBR) vs. load (in Erlangs) for different grooming OXCs under different bandwidth granularity distributions.

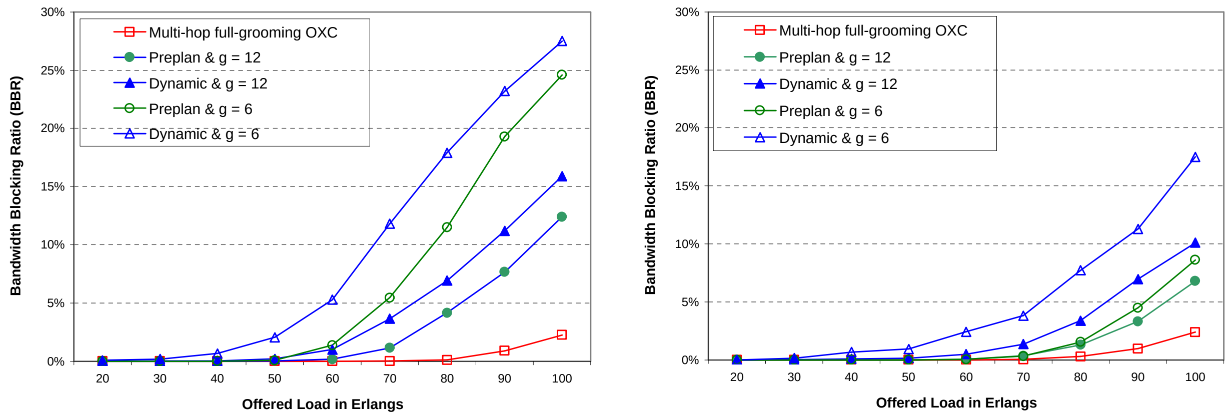
In Fig. 7, the multi-hop full-grooming OXC has shown the best network performance, and multi-hop non-grooming OXC shows another extreme case. We can observe that, (a) without employing any low-granularity multiplexing and switching functionality, lighttree-based source-node grooming OXCs can significantly improve network performance comparing with multi-hop non-grooming OXCs; (b) connection bandwidth-granularity distribution play an important role to the network performance. When there is a lot of low-speed connection requests, multi-hop full-grooming OXCs outperform multi-hop partial-grooming OXCs as shown in 7(a). As the number of high-speed connections increases, the performance gap between multi-hop full-grooming OXC is significantly reduced. Although not shown here, our experiment results verified that, when all connections require full-wavelength bandwidth granularity, those OXCs have the same network performance. Note that, the high BBR region shown in Fig. 7 may not be realistic in a practical WDM backbone network. They were shown for illustrative purpose to fairly compare the grooming OXCs' network performance under same offered load; (c) as shown in 7(d), the multi-hop full-grooming OXC perform almost the same under different bandwidth granularity distribution. On the other hand, for the other types of grooming OXCs, under the same network load, when there is more low-speed connections, the network performance will be worse. This is because that low-speed connections may potentially cause bandwidth waste and under-utilization of link-capacity when a network node does not have multi-hop full-grooming capability.

As we can see from Fig. 7, comparing with the multi-hop full-grooming OXC, the multi-hop partial-grooming OXC can have reasonable good network performance, while using significantly less amount of low-speed electronic processing. Besides the grooming policy and the corresponding grooming algorithm, the performance of multi-hop partial-grooming OXCs are determined by two factors:

- How many grooming capacity a multi-hop partial-grooming OXC can have.
- How to cost-effectively establish the multi-hop groomable lightpath (i.e., source-groomable lightpath, destination groomable-lightpath and full-groomable lightpath) to perform multi-hop grooming.

Hence, one approach to improve the performance of the multi-hop partial grooming OXC is to increase its grooming capacity. Recall that, the grooming capacity of a multi-hop partial-grooming OXC is determined by the size of G-fabric and is represented by the number of grooming ports (G-ports) connecting between the W-Fabric and the G-Fabric. Another approach is to optimize the establishment of multi-hop groomable lightpath. Those lightpaths can be either dynamically (on-demand) set up or be statically preplanned. In dynamic groomable-lightpath establishment approach, it is assumed that the future traffic pattern is unknown. Hence, instead of considering long-term global optimization, the groomable lightpath is set up according to the requirement of current connection request. On the other hand, groomable-lightpath preplan approach tries to pre-establish certain amount of groomable-lightpath based on the future traffic-demand projection. Low-speed connection requests are then dynamically provisioned using these preplanned resources. When all preplanned groomable lightpaths have been saturated, new groomable-lightpath can be dynamically established for current requests subject to network resource constraint.

Figure 8 shows how the number of grooming ports and how different groomable-lightpath establishment approaches may affect the network performance of a multi-hop partial-grooming OXC under different connection bandwidth-granularity distributions. In Fig. 8, g denotes the number of grooming ports a multi-hop partial-grooming OXC has. We can observe that, as g increases, the performance of multi-hop partial-



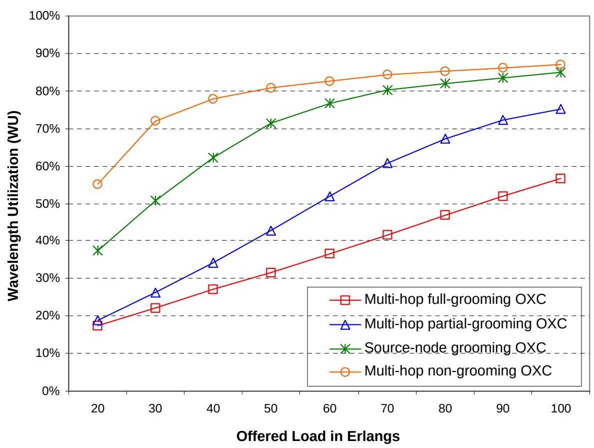
(a) $3:3:3:3:3$ (b) $1:1:1:1:1$

Fig. 8. The effect of preplanning multi-hop groomable-lightpath schemes and different number of grooming ports to the network performance in a WDM with multi-hop partial-grooming OXCs.

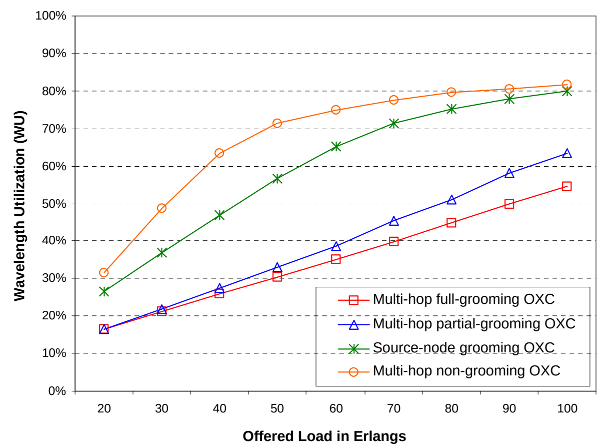
grooming improved. We have also simulated a very simple preplan scheme, called Embedded on Physical Topology (EPT). In EPT, full-groomable lightpaths are pre-established between every adjacent node pair. Those lightpaths form a grooming layer, which has exactly the same topology as the physical fiber topology. A low-speed connection will be carried by jointly utilizing the resource on this grooming layer as well as on physical topology through the grooming policies described in GUAG. Unlike a dynamic-established lightpath which will be teared down if it does not carry any traffic, a preplanned groomable lightpath will never be teared down. If one wavelength channel on every fiber link is used for EPT, we called it one degree EPT (1-EPT), which is simulated in out experiments. Figure 8 shows that, 1-EPT preplan scheme does improve the performance of multi-hop partial-grooming OXC comparing with dynamic groomable-lightpath establishment scheme. This is because that the dynamic scheme may greedily establish groomable-lightpath without considering the possible future traffic pattern. Although the GUAG algorithm try to perform local (or short-term) resource optimization, the grooming layer, which is formed by dynamic-established lightpaths, may not be optimal and efficient to carry the future requests. If every multi-hop partial-grooming OXC has enough grooming capability (i.e., enough grooming ports) and W-EPT is used, (where W is the number of wavelength channel supported by every fiber link), a network employing with multi-hop partial-grooming OXC will be equivalent to a network with multi-hop full-grooming OXC everywhere. Hence they will have the same network performance.

Note that, besides the grooming policy used in GUAG, applying other grooming policies may further improve the network performance, please see [13]-[14] for more possible grooming policies and their effect to network performance. Similarly, besides 1-EPT, other preplan schemes can also be used and it is possible for them to improve network performance. For example, the Integer Linear Program (ILP) formulation proposed in [11] can be used to preplan groomable lightpaths, and may achieve better network performance. A potential drawback of this approach is that it may not be scalable. This is because we may have to re-do the preplan procedure when the network need to be scaled or when the traffic pattern fluctuates. The study of other preplan schemes (2-EPT, ILP approach, etc), is beyond the scope of this paper, and will be addressed in our future study.

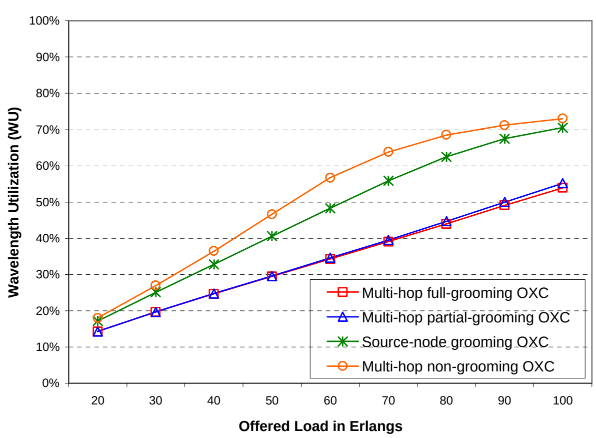
B. Wavelength Utilization



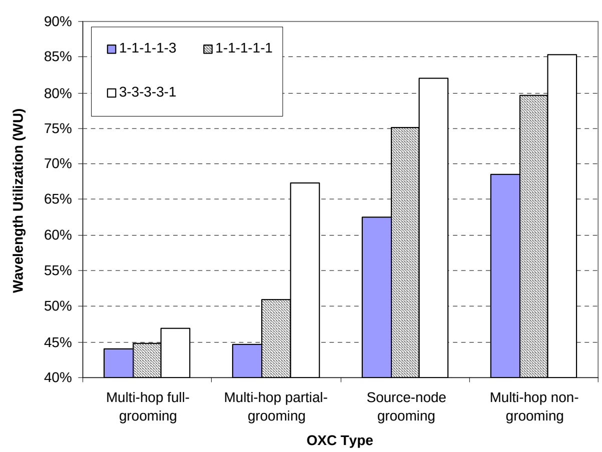
(a) $3:3:3:3:1$



(b) $1:1:1:1:1$



(c) $1:1:1:1:3$



(d) $Erlang = 80$

Fig. 9. Wavelength Utilization (WU) vs. load (in Erlangs) for different grooming OXCs under different bandwidth granularity distributions.

In Fig. 9, we plot the average (weighted by time) wavelength utilization (WU) versus network offered Erlang load for different grooming OXCs under different connection bandwidth-granularity distributions. WU represents the average number of used wavelength links over total number of wavelength links supported by the network during entire simulation period.

It is straight-forward to see that under the same network offered load, single-hop grooming OXCs will exhaust wavelength links more quickly than other OXC types. We can also observe from Fig. 9 that under the same network offered load, the more low-speed connections the network supports, the more wavelength links tend to be used. For the same bandwidth-blocking performance, a lower wavelength utilization is desirable since fewer wavelength links are consumed to carry the same load.

C. Resource Efficiency Ratio (RER)

Wavelength utilization shown in Fig. 9 may not be the best metrics to understand the resource usage of different grooming schemes and grooming OXCs. From Fig. 9, one can not tell that how efficiently those allocated wavelength channels are utilized. Resource efficiency ratio (RER) is a more suitable metric to understand the grooming performance of different OXCs and different grooming schemes. RER represents how efficiently connections are routed and groomed. It can be computed as the average (weighted by time) of network carried traffic (in terms of OC-1 unit) divided by the total allocated network capacity (i.e., total number of allocated wavelength link times 192) over the entire simulation period. If we consider "minimal hops" as our objective for a route-computation algorithm then the inverse of the average hop distance is the RER upper bound This upper bound is achieved only when every connection requires OC-192 bandwidth and follows the shortest path. Since there are limited resources (as in our case), not every connection can follow shortest path and the upper bound may not be achievable. Let α denote the RER, α can be computed as follows:

$$\alpha = \frac{\sum_i \rho_i \times t_i}{\sum_i \gamma_i \times t_i}$$

where t_i is the time period between the i^{th} event (connection arrival or departure) and $(i+1)^{th}$ event, ρ_i is the network carried load during the time period t_i, and γ_i is the total number of wavelength links used during t_i. (Please note that ρ_i and γ_i do not change during time period t_i as there is no other event during the period.)

Figure 10 shows the normalized resource efficiency ratio (RER) versus network offered load for different grooming OXCs under different bandwidth granularity distributions. The higher RER means that a network can route and groom traffic requests more efficiently. Hence, a network with high RER will have low bandwidth blocking ratio (BBR), which is shown in Fig. 7. This explained that, why under the same network offered load, the multi-hop full-grooming OXC use the least amount of wavelength channel (it has the lowest wavelength utilization) but carry the most amount of traffic (it has the lowest bandwidth blocking ratio). We can also observe from Fig. 10 that, under the same network offered load, when the number of low-speed connection increase, the resource efficiency ratio will decrease. This is because that increasing the number of connections will increase the difficulty for a network to fully utilize allocated wavelength channels, since the network resource are tend to be fragmented.

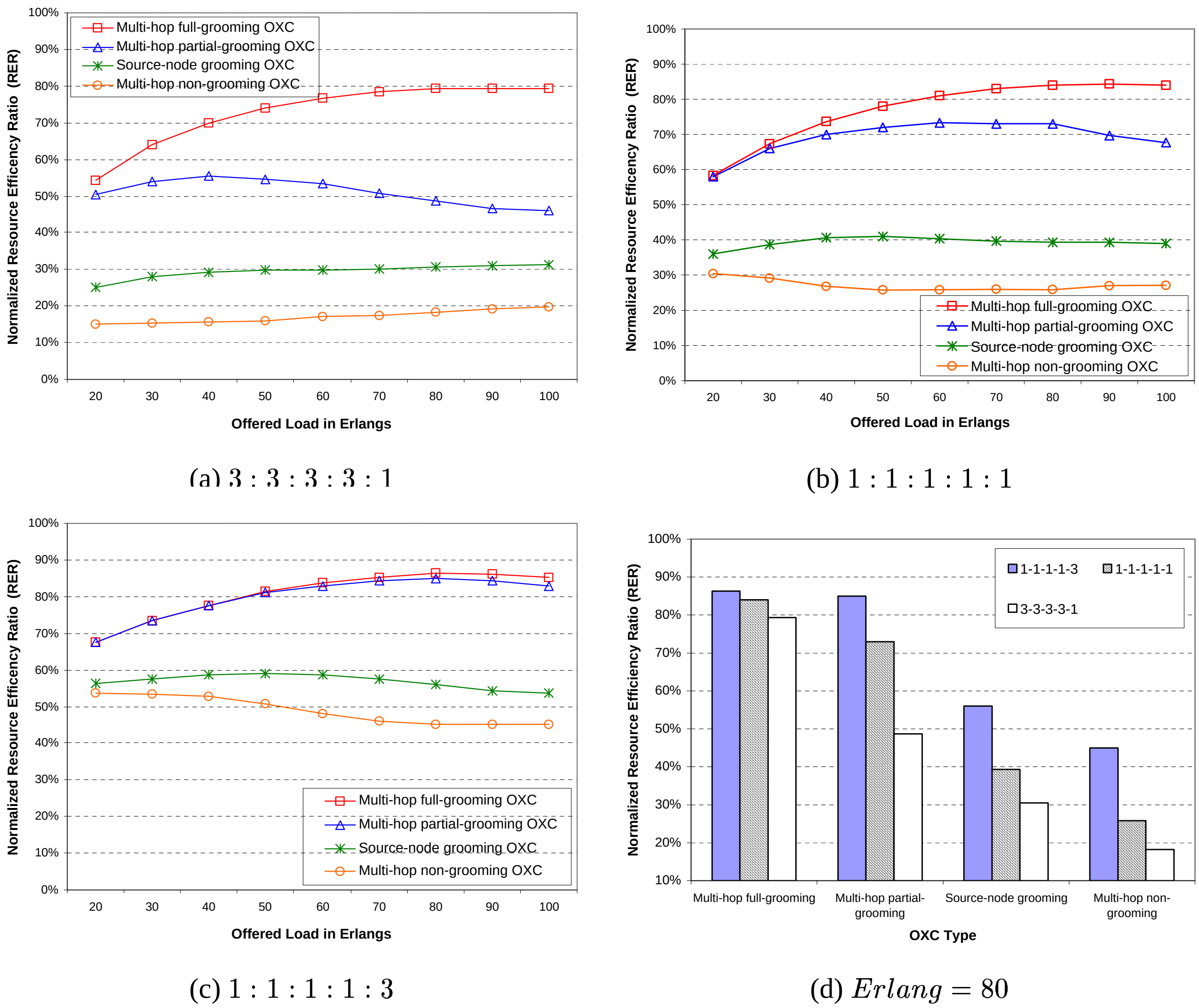


Fig. 10. Normalized Resource Efficiency Ratio (RER) vs. load (in Erlangs) for different grooming OXCs under different bandwidth granularity distributions.

V. Conclusions

In this study, we presented four optical grooming OXC architectures and compare their characteristics. Three grooming schemes, single-hop grooming, multi-hop grooming, and lighttree-based source-node grooming for those OXCs was explored. We proposed two algorithms, GUAG and GUL, to efficiently provision connections of different bandwidth granularities. The performance of different grooming OXCs was compared using the proposed algorithms under a dynamic traffic environment. We also investigate the effect of different bandwidth-granularity distributions to network performance of different grooming OXCs. We observe that, the lighttree-based source-node grooming using OXCs' multi-cast capability can significantly improve the network performance of single-hop grooming OXCs without employing any low-granularity electronic processing. The multi-hop full-grooming OXC always has the best network performance in term of network bandwidth blocking ratio, wavelength utilization, and resource efficiency ratio. But, it may encounter an scalability problem since huge amount electronic process are needed at low-speed granularity. With a few low-granularity switching capability, multi-hop partial-grooming shows reasonable good performance comparing with other grooming OXCs, which makes it as a good alternate choice when multi-hop full-grooming is not needed at every network nodes. In order to fairly compare the performance, a network is assumed to uniformly employ one type of grooming OXC. This assumption may not be practical and can be relaxed in next-generation optical backbone network, where different OXCs with different grooming capabilities may be inter-connected and co-exist. The proposed algorithms, GUAG and GUL, employ one traffic grooming policy and lighttree establishment approach. Other grooming algorithms with different traffic grooming policy and lighttree establishment approaches may also be examined, and will be our future research work.

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