A Review of Traffic Grooming in WDM Optical Networks: Architectures and Challenges*

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Abstract

The transmission capacity of a link in today's optical networks has increased significantly due to wavelength-division multiplexing (WDM) technology. The network performance is now mainly limited by the processing capability of the network elements, which are mainly electronic. By efficiently grooming low-speed traffic streams onto high-capacity optical channels, it is possible to minimize this electronic processing and eventually increase the network performance. Traffic grooming is an emerging topic that has been gaining more research and commercial attention. Most previous research on traffic grooming is mainly based on the ring network topology. It is expected that there will be much more interest on the mesh topology suitable for long-haul, wide-area networks. This paper reviews most of the recent research work on traffic grooming in WDM ring and mesh networks. Various network and node architectures for different traffic-grooming scenarios are compared and discussed.

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1. BACKGROUND

Optical wavelength-division multiplexing (WDM) is a promising technology to accommodate the explosive growth of Internet and telecommunication traffic in wide-area, metro-area, and local-area networks. A single optical fiber strand has the potential bandwidth of 50 THz. Using WDM, this bandwidth can be divided into multiple non-overlapping frequency or wavelength channels. Each WDM channel may be operated at any speed, e.g., peak electronic speed of a few gigabits per second (Gbps) [1, 2]. Currently, commercially available optical fibers can support over a hundred wavelength channels, each of which can have a transmission speed of over a gigabit per second (e.g., OC-48, OC-192, and OC-768 in the near future).

While a single fiber strand has over a terabit-per-second bandwidth and a wavelength channel has over a gigabit-per-second transmission speed, the network may still be required to support traffic connections at rates that are lower than the full wavelength capacity. The capacity requirement of these low-rate traffic connections can vary in range from STS-1 (51.84 Mbps or lower) up to full wavelength capacity. In order to save network cost and to improve network performance, it is very important for the network operator to be able to *"groom"* the multiple low-speed traffic connections onto high-capacity circuit pipes. Grooming is a term used to describe the optimization of capacity utilization in transport systems by means of cross-connections of conversions between different transport systems or layers within the same system [3].

Different multiplexing techniques can be used for traffic grooming in different domains of optical WDM networks.

- Space-division multiplexing (SDM) – partitions the physical space to increase transport bandwidth, e.g., bundling a set of fibers into a single cable, or using several cables within a network link [3].
- Frequency-division multiplexing (FDM) – partitions the available frequency spectrum into a set of independent channels. The use of FDM within an optical network is termed (dense) wavelength-division multiplexing (DWDM or WDM) which enables a given fiber to carry traffic on many distinct wavelengths. WDM divides the optical spectrum into coarser units, called wavebands, which are further divided into wavelength channels [3].
- Time-division multiplexing (TDM) – divides the bandwidth's time domain into repeated time-slots of fixed length. Using TDM, multiple signals can share a given wavelength if they are non-overlapping in time [3].
- Dynamic statistical multiplexing or packet-division multiplexing (PDM) – provides "virtual circuit" service in an IP/MPLS over WDM network architecture. The bandwidth of a WDM channel is shared between multiple IP traffic streams (virtual circuits).

Although most research on traffic-grooming problems in the literature concentrate on efficiently grooming low-speed circuits onto high-capacity WDM channels using a TDM approach, the generic grooming idea can be applied to any optical network domain using the various multiplexing techniques mentioned above.

Traffic grooming is composed of a rich set of problems, including network plannar, topology design (based on static traffic demand), and dynamic circuit provisioning (based on dynamic traffic demand). The traffic-grooming problem based on static traffic demands is essentially an optimization problem. It can be seen as a dual problem from different perspectives. One perspective is that, for a given traffic demand, satisfy all traffic requests as well as minimize the total network cost. The dual problem is that, for given resource limitation and traffic demands, maximize network throughput, i.e., the total amount of traffic that is successfully carried by the network.

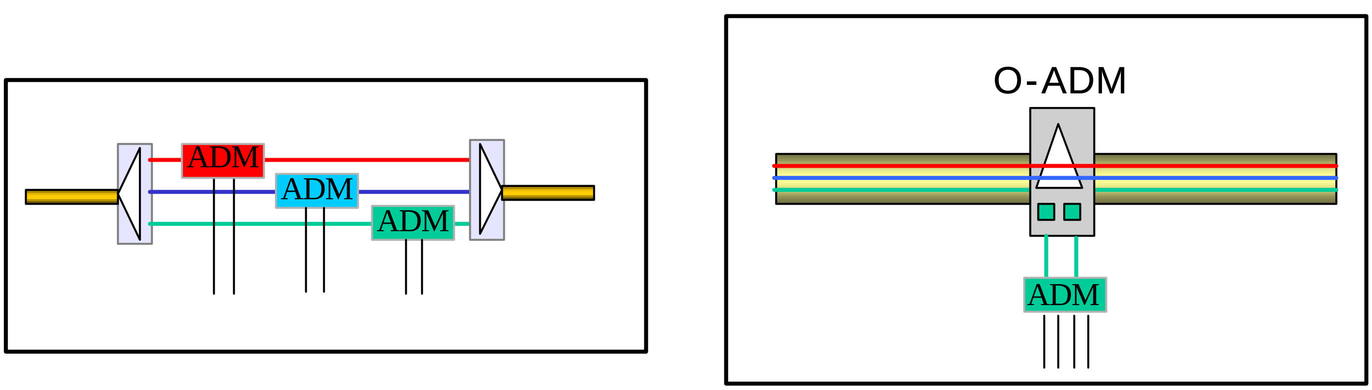
In recent years, there has been an increasing amount of research activity on the traffic-grooming problem, both in academe and in industry. Researchers are realizing that traffic grooming is a practical and important problem for WDM network design and implementation. In this paper, we review the state of the art of this research, both on SONET ring networks and on arbitrary-topology WDM mesh networks. Various network architectures are presented and discussed.

2. TRAFFIC GROOMING IN SONET RING NETWORKS

2.1. Node Architecture

SONET ring is the most widely used optical network infrastructure today. In a SONET ring network, WDM is mainly used as a point-to-point transmission technology. Each wavelength in such a SONET/WDM network is operated at OC-N line rate, e.g., N=48. The SONET system's hierarchical TDM schemes allow a high-speed OC-N channel to carry multiple OC-M channels (where M is smaller than or equal to N). The ratio of N and the smallest value of M carried by the network is called "*grooming ratio*". Electronic add-drop multiplexers (ADMs) are used to add/drop traffic at intermediate nodes to/from the high-speed channels.

In a traditional SONET network, one ADM is needed for each wavelength at every node to perform traffic add/drop on that particular wavelength. With the progress of WDM, over a hundred wavelengths can now be supported simultaneously by a single fiber. It is, therefore, too costly to put the same amount of ADMs (each of which has a significant cost) at every network node since a lot of traffic is only bypassing an intermediate node. With the emerging optical components such as optical add-drop multiplexers (O-ADM) (also referred to as wavelength add-drop multiplexers (W-ADM)), it is possible for a node to bypass most of wavelength channels optically and only drop the wavelengths carrying the traffic destined to the node. A fully optical wavelength circuit between the electronic components at a node pair is called a "*lightpath*".



(a) Without O-ADM (b) Without O-ADM

Figure 1. Node architectures in a SONET/WDM ring network.

Compared with the wavelength channel resource, ADMs form the dominant cost in a SONET/WDM ring network. Hence, carefully arranging these optical bypasses can reduce a large amount of the network cost. Figure 1 shows different node architectures in a SONET/WDM ring network. It is clear that using O-ADMs can decrease the number of SONET ADMs used in the network and eventually bring down the network cost. Then the problems are, for a given low-speed set of traffic demands, which low-speed demands should be groomed together, which wavelengths should be used to carry the traffic, which wavelengths should be dropped at a local node, and how many ADMs are needed at a particular node?

2.2. Single-Hop Grooming in SONET/WDM Rings

A SONET/WDM ring network can have the node architecture shown in Fig. 1(b). OC-M low-speed connections are groomed on to OC-N wavelength channels. Assume that there is no wavelength converter at any network node. The traffic on a wavelength cannot be switched to other wavelengths. Based on this network model, for a given traffic matrix, satisfying all the traffic demands as well as minimizing the total number of ADMs is a network design/optimization problem and has been studied extensively in the literature.

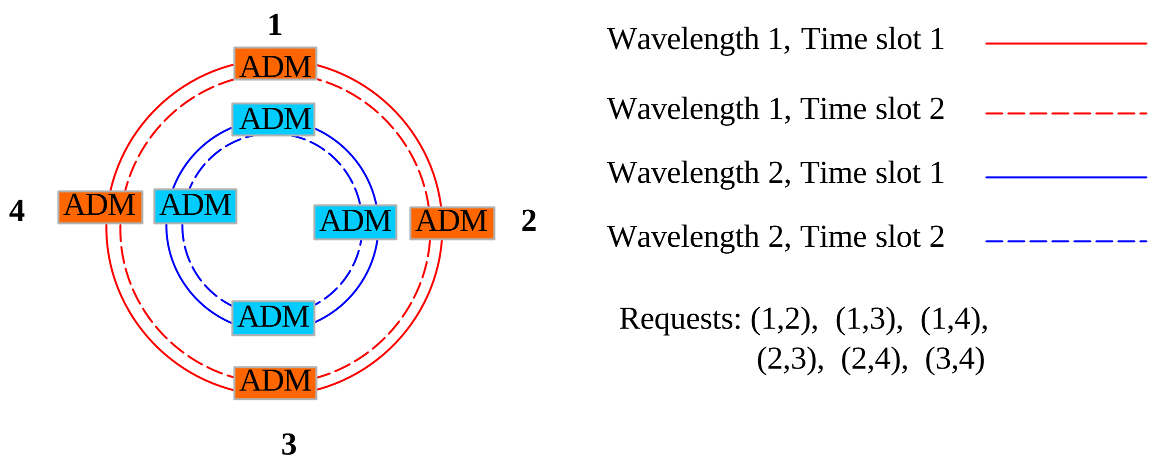


Figure 2. A SONET/WDM network with 4 nodes and 2 wavelengths.

Figures 2 and 3 show an example in which, by carefully grooming traffic in the SONET/WDM rings, some network cost savings can be achieved. Figure 2 shows a SONET/WDM ring network with 6 unidirectional connection requests. Each node is also equipped with an O-ADM (not shown in the figures). Assume that the SONET ring is also unidirectional (clockwise), the capacity of each wavelength is OC-N, and it can support two OC-M low-speed traffic requests in TDM fashion, i.e., N = 2M. In order to support all of the traffic requests, 8 ADMs are used in the network. Figure 3(a) shows a possible configuration. By interchanging the connections (1,3) and (2,3), wavelength 2 (red) can be optically bypassed at node 2, which results in one ADM savings at node 2. Figure 3(b) shows this configuration.

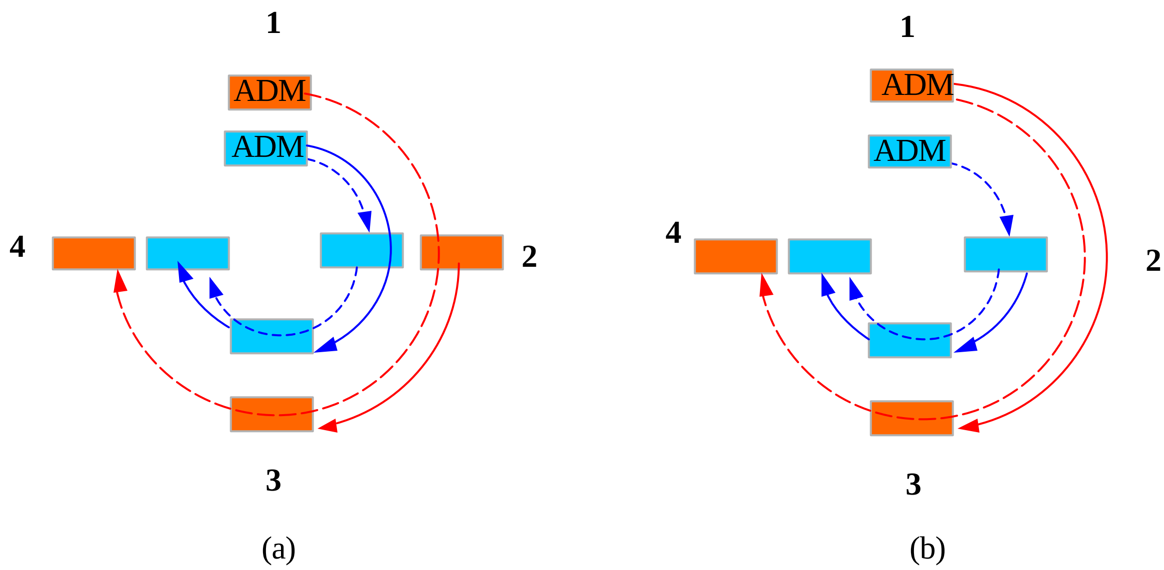


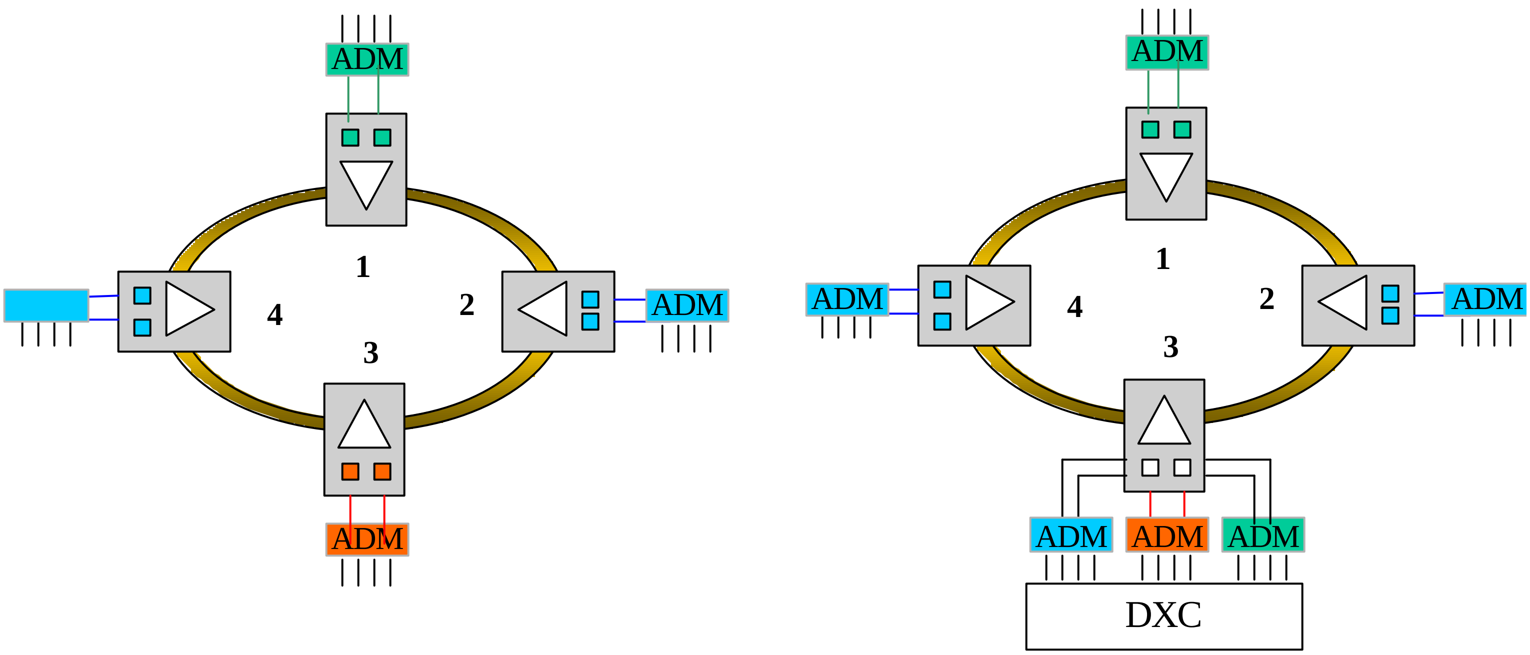
Figure 3. Two possible configurations to support the traffic requests in Fig. 2.

It has been proven in [4, 5] that the general traffic-grooming problem is NP-complete. The authors in [6] formulate the optimization problem as an integer linear program (ILP). When the network size is small, some commercial software can be used to solve the ILP equations to obtain an optimal solution. The formulation in [6] can be applied to both uniform and non-uniform traffic demands, as well as to unidirectional and bi-directional SONET/WDM ring networks. The limitation of the ILP approach is that the numbers of variables and equations increase explosively as the size of the network increases. The computation complexity makes it hard to be useful on networks with practical size. By relaxing some of the constraints in the ILP formulation, it may be possible to get some results, which are close to the optimal solution for reasonable-size networks. The results from the ILP may give some insights and intuition for the development of good heuristic algorithms to handle the problem in a large network.

In [5, 7, 8], some lower-bound analysis is given for different traffic criteria (uniform and non-uniform) and network model (unidirectional ring and bi-directional ring). These lower-bound results can be used to evaluate the performance of traffic-grooming heuristic algorithms. In most of the heuristic approaches, the traffic-grooming problem is divided into several sub-problems and solved separately. These heuristics can be found in [4-9]. Greedy approach, approximation approach, and simulated annealing approach are used in these heuristic algorithms.

2.3. Multi-Hop Grooming in SONET/WDM Ring

In single-hop (a single-lightpath hop) grooming, traffic cannot be switched between different wavelengths. Figure 4(a) shows this kind of a network configuration. Another network architecture has been proposed in [8, 10], in which there are some nodes equipped with Digital Crossconnects (DXCs). In Fig. 4(b), node 3 has a DXC installed. This kind of node is called a hub node. Traffic from one wavelength/time-slot can be switched to any other wavelength/time-slot at the hub node. Because the traffic needs to be converted from optical to electronic at the hub node when wavelength/time-slot exchange occurs, this grooming approach is called multi-hop (multi-lightpath hops) grooming. Depending on the implementation, there can be a single hub node or multiple hub nodes in the network. A special case is that every node is a hub node, i.e., there is a DXC at every node. This kind of network is called *point-to-point* WDM ring network (PPWDM ring) [10].



(a) Single-hop (without hub node)

(b) Multi-hop (with a hub node)

Figure 4: SONET/WDM ring with/without a hub node.

The work in [10] provides some excellent theoretical analysis on comparing network cost of PPWDM ring, a SONET/WDM ring without hub node, a SONET/WDM ring with one or multiple hub nodes, etc. The authors of [6] have compared the single-hop grooming with multi-hop grooming (with one hub node) network performance using simulation. The results indicate that, when the grooming ratio is large, the multi-hop approach tends to use fewer ADMs, but when the grooming ratio is small, the single-hop approach tends to use fewer ADMs, and in general, the multi-hop approach uses more wavelengths than the single-hop approach.

2.4. Dynamic Grooming in SONET/WDM Ring Networks

Instead of using a single static traffic matrix to characterize the traffic requirement, it is also possible to describe it by a set of traffic matrices. The traffic pattern may change within this matrix set over a period of time, say throughout a day or a month. The network needs to be reconfigured when the traffic pattern transits from one matrix to another matrix in the matrix set. The network design problem for supporting any traffic matrix in the matrix set (in a non-blocking manner) as well as minimizing the overall cost is known as a *dynamic grooming problem* in a SONET/WDM ring [11].

Unlike the dynamic provisioning and grooming problem in a WDM mesh network, which will be introduced in Section 3, the dynamic-grooming problem proposed in [11] is more likely a network design problem with reconfiguration consideration. The authors of [11] have formulated the general dynamic-grooming problem in a SONET/WDM ring as a bipartite graph-matching problem and provided several methods to reduce the number of ADMs. A particular traffic matrix set is then considered and the lower bound on the number of ADMs is derived. They also provide the necessary and sufficient conditions so that a network can support such a traffic pattern. This kind of traffic matrix set is called a *t-allowable* traffic pattern. For a given traffic matrix, if each node can source at most t duplex circuits, we call this traffic matrix a t-allowable traffic matrix. The traffic matrix set, which only consist of t-allowable traffic matrices, is called a t-allowable matrix set or a t-allowable traffic pattern. We use an example from [12] to illustrate dynamic traffic grooming for a t-allowable traffic pattern in a SONET/WDM ring.

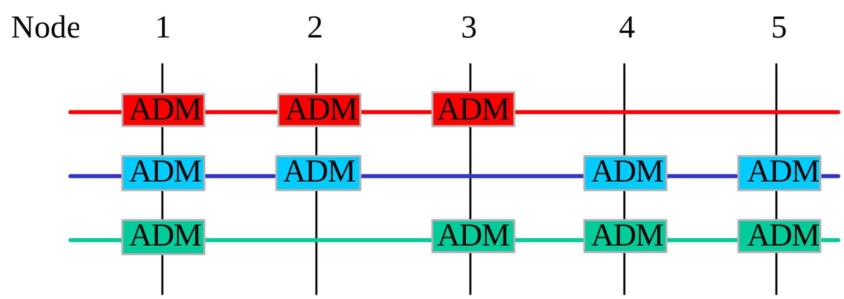


Figure 5. Network design for 2-allowable traffic.

Figure 5 shows a 5-node SONET/WDM ring network. Three wavelengths are supported in the network. Assume that each wavelength can support 2 low-speed circuits. The network configuration in Fig. 5 is a 2-allowable configuration, i.e., it can support any 2-allowable traffic matrix (set). For instance, consider a traffic matrix with request streams {1-2, 1-3, 2-3, 2-4, 3-4, 4-5, 4-5}. The traffic matrix can be supported by assigning {1-3, 2-3} on red wavelength, assigning {1-2, 2-4, 4-5, 4-5} on blue wavelength, and assigning {3-4} on green wavelength. Note that, for a particular traffic matrix, there may be some redundant ADMs in the configuration. However, the configuration is able to support other potential t-allowable traffic matrices. Designing such configurations to support any t-allowable traffic matrix while minimizing the network cost is a very interesting research problem. The authors in [11] provide an excellent analysis on t-allowable traffic pattern. The study of dynamic-traffic grooming in a SONET/WDM ring with other generic traffic pattern can be potentially challenging research.

2.5. Grooming in Interconnected SONET/WDM Rings

Most traffic-grooming studies in SONET/WDM ring networks have assumed a single-ring network topology. The authors of [13] have extended the problem to an interconnected-ring topology. Today's backbone networks are mainly constructed as a network of interconnected rings. Extending the traffic-grooming study from a single-ring topology to the interconnected-ring topology will be very useful for a network operator to design their network and to engineer the network traffic.

Figure 6(a) shows an interconnected SONET/WDM ring network with a single junction node. Multiple junction nodes may also exist in the interconnected-ring topology because of network survivability consideration. Various architectures can be used at the junction node to interconnect the two SONET rings. Figures 6 (b)-(d) [13] show some of the node architectures.

In Fig. 6(b), an O-ADM is used to drop some wavelengths at the junction node. ADMs and a DXC are used to switch the low-speed circuits between the interconnected rings. This node architecture has wavelength-conversion and time-slot-interchange capability, i.e., a time slot (low-speed circuit) on one wavelength can be switched to another time slot on a different wavelength through this junction node.

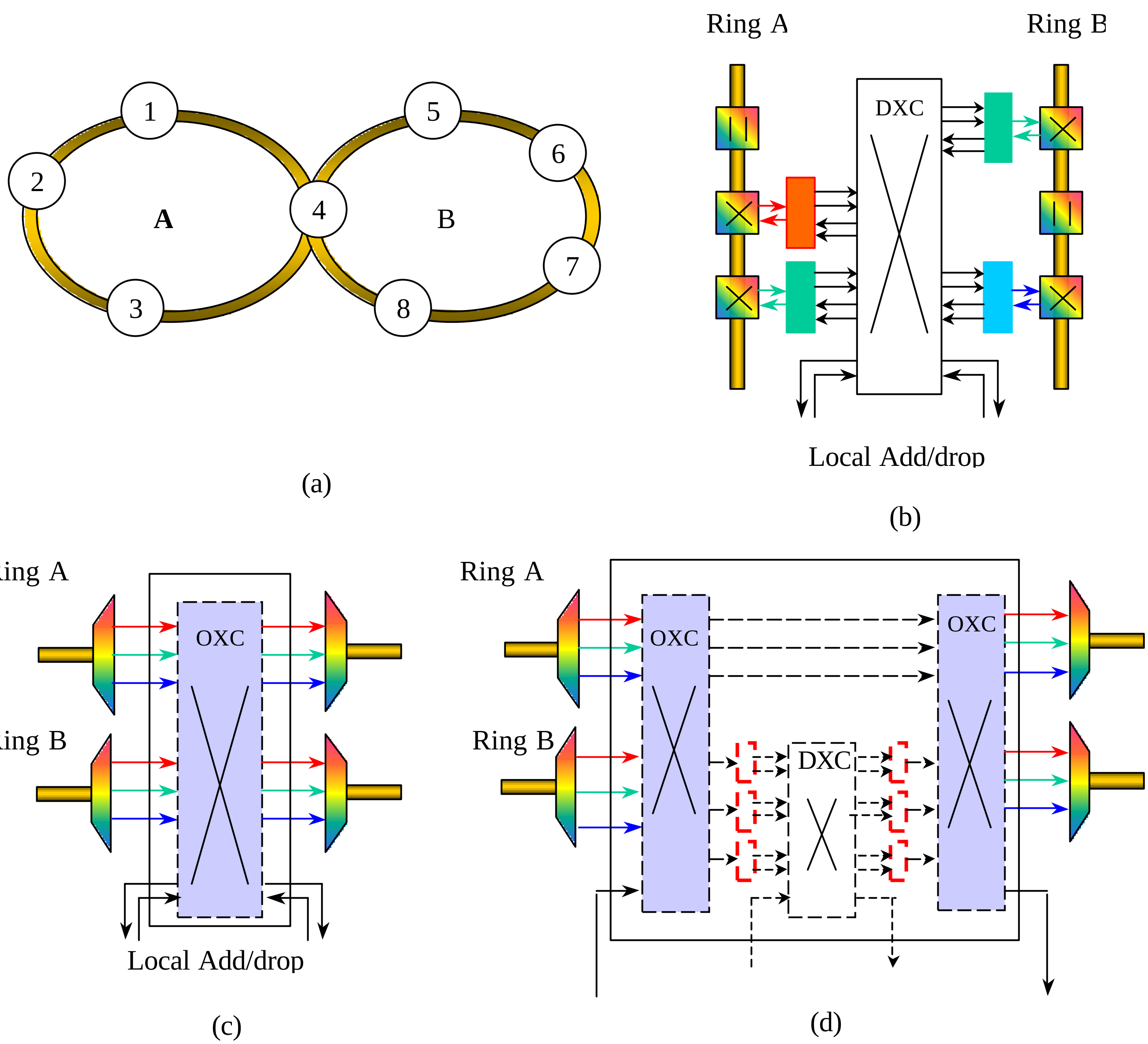


Figure 6. A sample interconnected-ring network topology and simplified architectures of the junction node.

Figure 6(c) uses an Optical Crossconnect (OXC) to interconnect the two rings. There are transparent and opaque technologies to build these OXCs. Transparent refers to all-optical switching, and opaque refers to switching with optical-electronic-optical (O-E-O) conversion. Depending on the implementation, the OXC may be equipped with or without wavelength-conversion capability. This node architecture can only switch the traffic at the wavelength granularity between the interconnected rings. Note that extra ADMs are needed to support local traffic originating from or terminating at the junction node.

Figure 6(d) shows a hierarchical node architecture with a switching capability on both wavelength and lower-speed circuit granularity.

The different node architectures at the junction nodes in the interconnected-ring network will add different constraints to the traffic-grooming problem. The work in [13] presented the ILP formulation of the traffic-grooming problem in an interconnected-dual-ring topology, and proposed a heuristic algorithm to handle the problem for networks of practical size. Results are compared between the various junction nodes' interconnection strategies and grooming ratios. When the number of rings and the number of junction nodes increase in the interconnected-ring network, the network topology tends to become an irregular mesh topology.

Section 3 discusses some recent studies on traffic grooming on the WDM mesh topology. A comparison between the interconnected-ring approach and the mesh approach will be a potential research challenge and hasn't been explored in the literature yet.

3. TRAFFIC GROOMING IN WAVELENGTH-ROUTED WDM MESH NETWORKS

Most previous work on traffic grooming in the optical network literature is based on the ring network topology. Recently, traffic grooming in a WDM mesh network has started to get more attention. In this section, we review some recent work, which have been reported on this subject. We will also show some potential research challenges and directions.

3.1. Network Provisioning: Static and Dynamic Traffic Grooming

Although the SONET (interconnected) ring network has been used as the first generation of the optical network infrastructure, it has some limitations, which make it hard to scale and to accommodate the increasing Internet traffic. The next-generation optical network is expected to be an intelligent wavelength-routed WDM mesh network. This network will provide fast and convenient (point-and-click) automatic bandwidth provisioning and efficient protection mechanisms; and it will be based on an irregular mesh topology, which will make it much easier to scale.

When such a network is constructed, how to efficiently accommodate the incoming traffic requests is a network-provisioning problem. The traffic request can be static (measured by one or multiple fixed traffic matrices) or dynamic (measured by the arrival rate and the holding time statistics of a connection request). The work in [14], based on static traffic demands, discusses the node architectures in a WDM mesh network, which has traffic-grooming capability.

Figure 8 shows such an OXC architecture, which has hierarchical switching and multiplexing functionality. Instead of using a separate wavelength-switching system and a grooming system (Fig. 6(d)), the OXC in Fig. 8 can directly support low-speed circuits and groom them onto wavelength channels through a grooming fabric (G-Fabric) and built-in transceiver arrays. This kind of OXC is named as Grooming OXC (G-OXC) or Wavelength-Grooming Crossconnect (WGXC) [15]. In a network equipped with a G-OXC at every node, the grooming fabric and the size of the transceiver array provide another dimension of constraints on the network performance besides the wavelength-resource constraint. This is similar to the ADM constraint for traffic grooming in SONET/WDM ring networks.

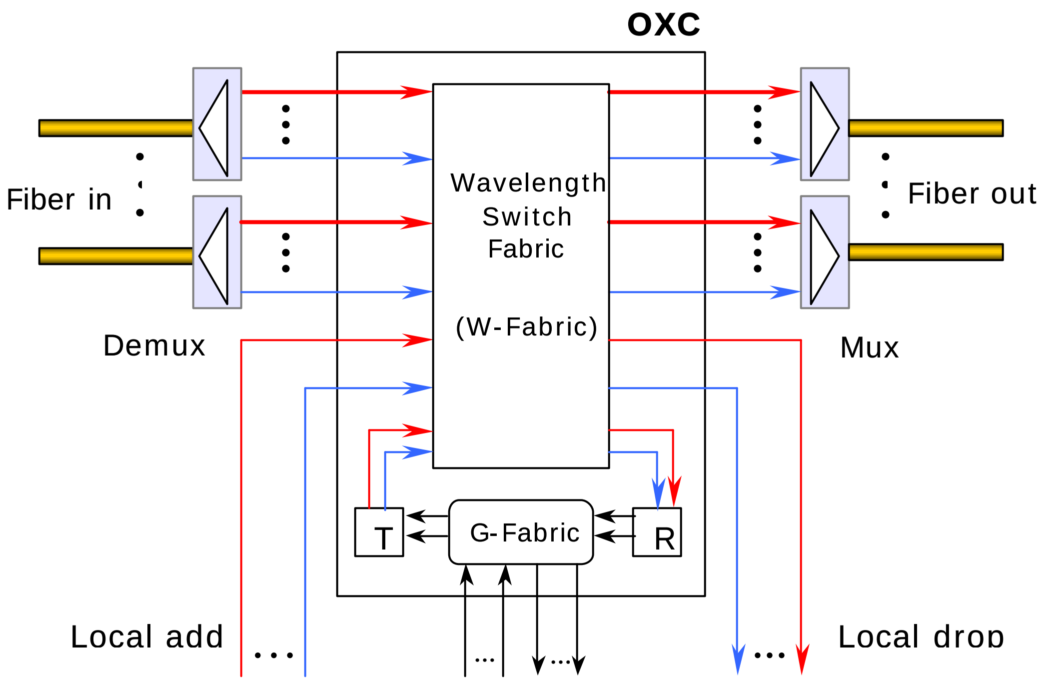


Figure 8: An OXC with grooming capability.

The transceiver array used in the OXC can be either tunable or fixed. The authors in [14] consider a static traffic matrix set as the network traffic demands. Each traffic matrix in the matrix set represents a particular low-speed circuit request class. For given network resource constraints and traffic demands, the work in [14] studies how to maximize the network throughput under the network resource limitation. As stated in Section 1, minimizing cost and maximizing network throughput lead to two different perspectives on the same traffic-grooming problem. The authors in [14] formulate the problem as an ILP. A small network is used to show ILP results and two heuristic algorithms are proposed to study larger networks based on the observations from these results. Different network scenarios are considered and compared in [14]. They are single-hop grooming vs. multi-hop grooming, tunable transceivers vs. fixed transceivers, optimizing network throughput vs. optimizing network revenue, etc.

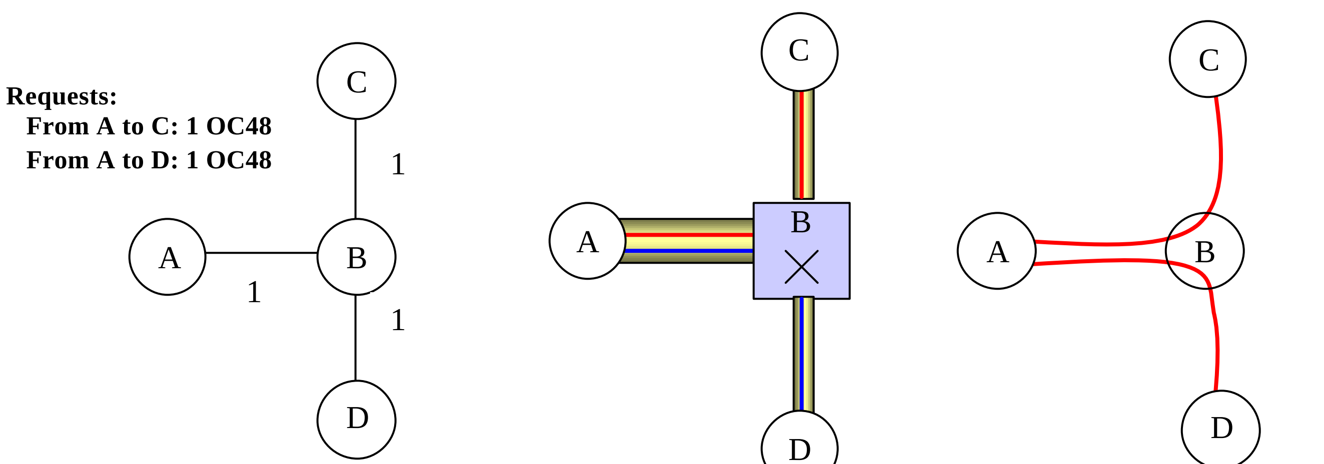
Unlike the work in [14], the works in [15, 16] consider a dynamic traffic pattern in a WDM mesh network. The work in [15] has proposed a connection admission control (CAC) scheme to ensure that the network will treat every connection fairly. It has been observed in [15] that, when most of the network nodes have grooming capability, the high-speed connection requests will have higher blocking probability than the low-speed connection requests in the absence of any fairness control. CAC is needed to guarantee that every class of connection requests will have similar blocking probability performance. The work in [16] proposed a theoretical capacity-correlation model to compute the blocking probability for WDM networks with constrained grooming capability.

The work in [14] has assumed that every node is a WGXC node, and the grooming capability is constrained by the grooming fabric and transceiver array at every node. The work in [15] has assumed that only a few of the network nodes are WGXC nodes and there is no constraint on these nodes. It will be a good extension to combine these assumptions and study the network performance as well as fairness in a static as well as a dynamic environment. This extension will be very practical and important to a service provider.

3.2. Network Design and Plannar

Unlike the network-provisioning problem addressed in Section 3.1, the work in [17] studied how to plan and design such a WDM mesh network with certain forecast traffic demands. The problem is a network design and plannar methodology. The problem description is as follows: given forecast traffic demand (static) and network node (locations), determine how to connect the nodes using fiber links and OXCs and route the traffic demands in order to satisfy all of the demands as well as minimize the network cost. The network cost is measured by the fiber cost, OXC or DXC port cost, and WDM system cost used in the network.

Figure 7 (from [17]) gives an example on this network design and plannar problem considering traffic grooming. Figure 7(a) shows a four-node network and the traffic demands. Each link in Fig. 7(a) is a fiber conduit, which may carry multiple fiber links. Assume that the cost of a fiber going through one conduit is one unit and the capacity of a wavelength channel is OC-48. Five segments exist in Fig. 7(a): (A, B), (A, C), (A, D), (B, C), and (B, D). A segment is a sequence of fiber links that does not pass through an OXC [17]. There are two possible network design options to accommodate the traffic demands, which are shown in Figs. 7(b) and 7(c).



(a) Node and fiber conduit location (b) Design option 1 (c) Design option 2

Figure 7: Two different designs for a 4-node network [17].

Option 1 (Fig. 7(b)):

- ?? Place a fiber on segments (A, B), (B, C), and (C, D).
- ?? Install a WDM system on each fiber.
- ?? Place an OXC with 4 ports at node B to interconnect the wavelength channels.
- ?? There will be a total of 4 OXC ports used at nodes A, C, and D to add and drop traffic.

Total cost for option 1 will be:

Cost (option 1) = 3 unit fiber cost + 3 WDM systems + 8 OXC ports (overall)

The two demands will be carried by the red wavelength and blue wavelength shown in Fig. 7(b).

Option 2 (Fig. 7c)):

- ?? Place a fiber on segments (A, C) and (A, D). These fibers will bypass node B.
- ?? Install a WDM system on each fiber.
- ?? There will be a total of 4 OXC ports used at nodes A, C, and D to add and drop traffic.

Total cost for option 2 will be:

Cost (option 2) = 4 unit fiber cost + 2 WDM systems + 4 OXC ports (overall)

The two demands will be carried by the red wavelengths shown in Fig. 7(c).

From this example, we can see that each network element has its own cost function and the definitions of these cost functions will eventually determine how the network should be designed.

The authors in [17] have addressed this network design and plannar problem. The problem is formulated as an ILP. Two heuristic algorithms are proposed for the mesh network design and the ring network design separately, i.e., design the network as an irregular mesh topology or an interconnected-ring topology. The authors compare the results between the mesh design and ring design. They find that (a) the mesh topology design has a compelling cost advantage for sufficiently large distance scales; (b) for ring technologies such as OC-192 BLSR, using WDM only results in cost savings when distances are sufficiently large; and (c) costs can be very insensitive to distance for ring technologies [17].

3.3 Grooming with Protection Requirement in WDM Mesh Networks

The SONET/WDM ring networks have been proven to have reliable link-protection schemes. There is no need to consider the protection issue separately for groomed traffic in such a network. On the other hand, protection for groomed traffic should be studied in WDM mesh networks.

In a WDM mesh network, various protection schemes can be used depending on the network operator's preference and the customer's requirements. Either link-protection scheme or path-protection scheme may be applied on a WDM mesh network, and the protection resources can be dedicated or shared by the working circuits. Although WDM protection schemes in mesh networks have been studied extensively, protection with traffic grooming is an open research area and needs to be carefully addressed.

Different low-speed circuits may ask for different bandwidth requirement as well as protection service requirement. The low-speed circuits may be protected on either the electronic layer or on the optical layer. Figure 9 (from [18]) shows an example of path protection in a network with electronic layer and optical layer. In Fig. 9, the green nodes are the nodes which are equipped with OXCs. Lightpaths can be established between these nodes, and low-speed connections can be groomed onto these lightpaths and transmitted in the optical domain.

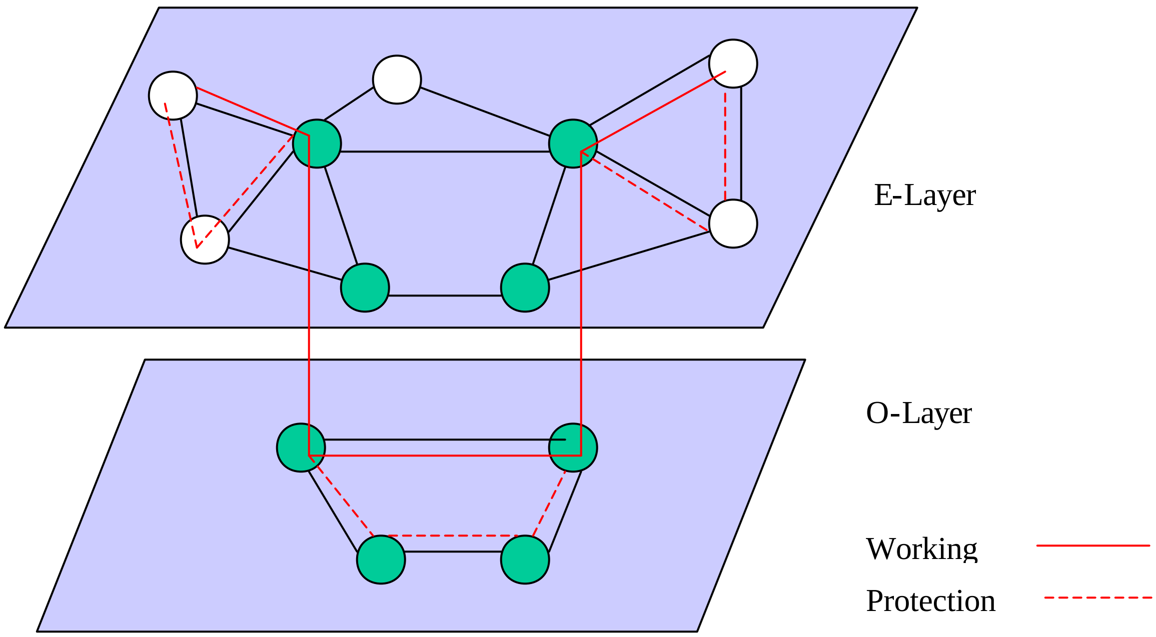


Figure 9: A multi-layer protection example [18].

Given a static traffic matrix and the protection requirement for every request (no protection, 1+1 protection, m:n protection, etc.), the authors in [18] studied how to satisfy these connections' bandwidth and protection requirements while minimizing the network cost. Network cost is determined by the transmission cost and switching cost in a manner similar to that described in Section 3.2. The bandwidth requirement of a connection can be a fraction of a wavelength channel and some connections may be partially carried by the electronic network layer. The authors of [18] show how much benefit there will be on network cost by grooming the traffic onto the optical domain instead of carrying them purely on the electronic layer. An ILP formulation is given and a simple heuristic is proposed. We believe that it is possible to improve the heuristic and its performance presented in [18]. The study of traffic grooming with protection requirement in a dynamic environment is a challenge and interesting topic.

3.4. Grooming with Multicast in WDM Mesh Networks

Multicast applications such as video-on-demand and interactive games are becoming more and more popular. It is reasonable to estimate that there will be more such multipoint applications which may require vast amount of bandwidth in the near future such as video conferencing, virtual reality entertainment, etc. Optical multicasting using "*light-tree*" [19] may be a good solution for these requirements. Since each wavelength will have capacity up to OC-192 (OC-768 in the future), multiple multicast sessions can be groomed to share the capacity on the same wavelength channel. In this case, the lightpaths or the light-trees can be established to accommodate multicast requests, which have lower capacity requirement than the bandwidth of a wavelength.

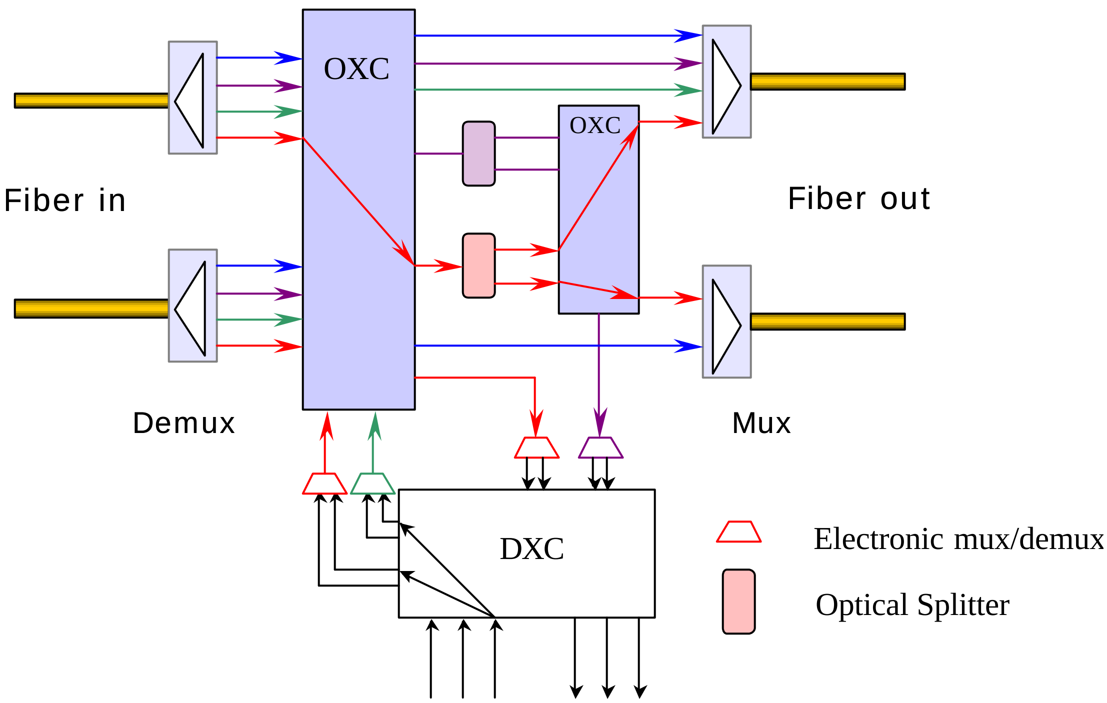


Figure 10: Switch architecture for supporting multicast grooming [19].

Figure 10 shows a simplified switch architecture, which can support multicast sessions with full wavelength capacity requirement or partial wavelength capacity requirement. With this architecture, the data on a wavelength channel from one incoming fiber or the local node can be switched to multiple outgoing fibers, and a full wavelength channel multicasting session can be maintained as much as possible in the optical domain. The DXC in Fig. 10 has multicast capability. This kind of electronic switch fabric is already commercially available. By combining this DXC with OE/EO conversion components (electronic mux/demux and transceiver), a low-speed multicast session can be groomed with other low-speed unicast/muticast sessions.

The work in [20] reports on some preliminary studies on multicast grooming in WDM mesh networks. The problem is defined as follows: given a set of multicast sessions with various capacity requirements, satisfy all of the multicast sessions, and at the same time, minimize the network cost. The network cost is measured by the wavelength-link cost used in the network. The authors of [20] show an ILP formulation for this problem and present some results based on some sample traffic matrices and network topologies. It is hard to scale the ILP approach to handle networks of practical size. Hence, simpler and efficient algorithms need to be explored to achieve near-optimal solutions. Multicast with grooming is a new research area and is expected to receive more attention in the optical networking literature.

3.5. Protocols and Algorithm Extensions for WDM Network Control

Traffic grooming is a very important problem whose solution will enable us to fully develop an intelligent WDM optical transport network. The unified control plane of such a network is being standardized, and is known as Generalized Multi-Protocol Label Switching (GMPLS) [21] in the Internet Engineering Task Force (IETF) forum. The purpose of this network control plane is to provide an intelligent, automatic, end-to-end circuit (virtual circuit) provisioning/signaling scheme throughout the different network domains. Different multiplexing techniques such as

PDM, TDM, WDM, and SDM may be used for such an end-to-end circuit, and good grooming schemes are needed to efficiently allocate network resources.

There are three components in the control plane that need to be carefully designed to support traffic grooming, namely, resource-discovery protocol, signaling protocol, and path-computation algorithms. Several resource discovery protocols based on traffic engineering (TE) extensions of link-state protocols (OSPF, IS-IS) [22-24] and link-management protocols [25] have been proposed in IETF as the resource-discovery component in the control plane. The extensions of the MPLS signaling protocols are proposed as the signaling protocol in this control plane. An open issue is the design of efficient route-computation algorithms. The work in [26, 27] has reported some preliminary result on on-line schemes to provision connections with different bandwidth granularities (i.e., dynamic traffic grooming) in WDM mesh networks, which employ the GMPLS distributed control plane. Various *grooming policies* have been proposed. A grooming policy reflects the intension of a network operator on how to engineer network traffic. It has been shown that, in order to achieve good performance in a dynamic environment, different grooming polices and route-computation algorithms need to be used under different network states.

4. CONCLUSION

The objective of this paper was to provide an overview of the architectures and the research activity on traffic grooming in WDM optical networks. Some problems on traffic grooming have been well studied (e.g., grooming in SONET rings), and some are open (e.g., grooming in mesh networks). We expect that there will be more interesting research on this topic.

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