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DYNAMIC TRAFFIC GROOMING: THE CHANGING ROLE OF TRAFFIC GROOMING

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ABSTRACT

Traffic grooming refers to the techniques used to aggregate subwavelength traffic onto high speed lightpaths, while at the same time minimizing some measure of network cost, usually optoelectronic equipment cost. In the last few years, traffic grooming has come to be recognized as an important research area, and has produced extensive literature. Recently, the dynamic traffic grooming problem, where traffic carried in the network varies with the time, has gained in interest. This is because of the growing applicability of QoS concerns and associated network design methodologies in networks closer to the individual users than backbone networks, where the traffic cannot be well modeled as essentially static. A number of studies in this area have recently appeared in the literature, but there is as yet no good resource that introduces a reader to the problem in all its forms, and provides a review of the literature. In this article, we fill this void by presenting a comprehensive survey of the literature in this emerging topic, and indicating some essential further directions of research in dynamic traffic grooming.

Computer and communication networking have been maturing over the past several decades, and has moved beyond the age of survival to the age of sophistication. The expectations of the end user from the network have also changed, and the concept of Quality of Service (QoS) and Service Level Agreements (SLA) have become pervasive. Until recently, it was assumed that such concerns were operative primarily in transport networks, that is at the highest level of aggregation of traffic in the planetary network hierarchy. At lower levels of aggregation, the network was seen to be composed of traffic networks, where QoS was neither feasible nor desired.

In this context, *traffic grooming* became an active area of research starting from the late 1990s. The new generation optical networks utilizing Wavelength Division Multiplexing (WDM) are currently in the process of being deployed to form the backbone networks of tomorrow. In WDM, multiple wavelength channels can be used over the same physical link of optical fiber using frequency multiplexing. Each wavelength channel can carry 10 Gb/s with current technology, and higher rates are foreseen for the near future. Further, *wavelength routing* technology makes it possible to forward an optical signal at an intermediate node entirely at the optical plane, forming clear end-to-end optical channels that are called *lightpaths*. WDM networks utilizing wavelength routing can be modeled as multi-layer networks that consist of a virtual layer formed by such lightpaths implemented over a physical topology of optical fiber, and customer traffic routed at a second level, over the lightpaths of the virtual topology. The customer traffic demands are expected to be generally of much smaller bandwidth than the capacity of a single wavelength channel. Moreover, the traffic demands will be various different rates. For example, in generalized MPLS (GMPLS) [1, 2] networks, the traffic carried by this virtual layer are label switched paths, which can be of arbitrary bandwidth requirements. Because of the significant disparity between the typical bandwidth request of a traffic component and the much higher capacity of a wavelength, it is well recognized that, to reduce the network cost, low speed traffic (referred to as subwavelength traffic) must be multiplexed (using Time Division Multiplexing) into lightpaths.

However, wavelength routing only allows the entire wavelength channel to be switched at the optical plane. If differen-

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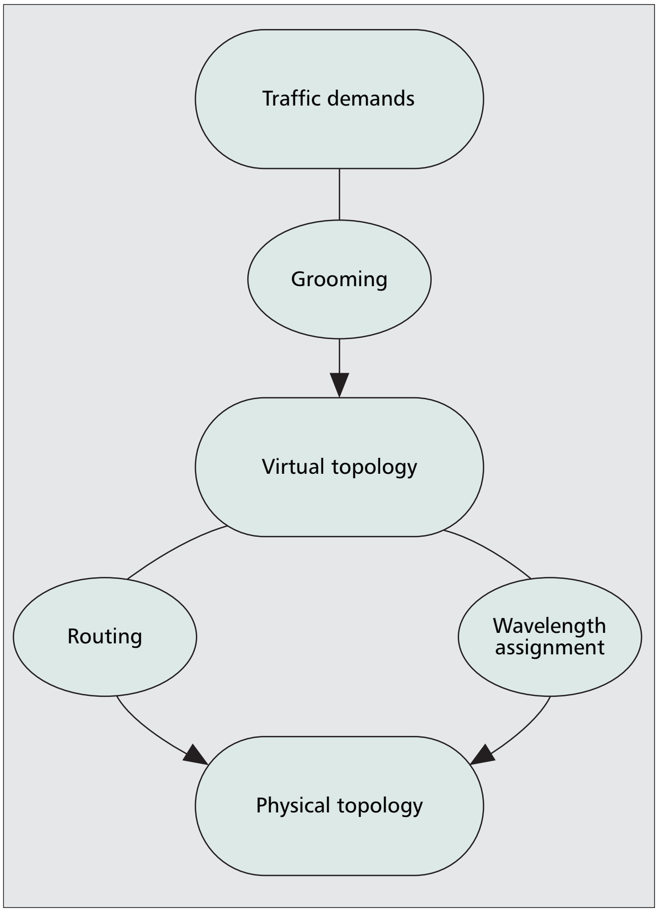

Figure 1. *Dynamic traffic grooming subproblems.*

tiated routing and forwarding of subwavelength traffic components contained in a wavelength channel is required, the optical signal must be terminated using Line Terminating Equipment (LTE), converted into digital electronic signals, and input to an electronic logic device such as a traditional electronic router. At the end of the electronic routing operation, the packets must again be converted to optical signal and injected into outgoing lightpaths. This operations is called Opto-Electro-Optic (OEO) conversion, and is generally not desirable because it offsets the high speed and reliability of optical transport, and the OEO device is significantly more expensive than the optical switching equipment. Thus the subwavelength traffic must be packed into full wavelengths such that the cost of such OEO conversion may be optimized globally. This is the problem usually referred to as traffic grooming. The reader is referred to [3] for a survey.

In this literature, researchers have generally assumed that the magnitudes of traffic demands (given as a single traffic matrix) do not change with time. This assumption is reasonable for the following two reasons. First, in many core networks, low speed traffic requests are aggregated over several hierarchical levels of networks, and at many levels the bandwidth of the higher level network is sufficient to carry the aggregated flows from the tributary networks in terms of the average rates, but not the peak rates. Thus there is periodic buffer buildup and drainout, leading to some smoothing of traffic burstiness in such networks. Second, because of the importance of high speed traffic demands (in terms of the revenue the carrier will obtain), the network is designed such that the peak rates of traffic demands, which do not change drastically, are satisfied. Both reasons make the problem amenable to the static analysis.

However, recently the usefulness of the static approach has been seen as having clear limitations. As WDM optical networks are being deployed not only in Wide Area Networks (WAN) but also in Metropolitan Area Networks (MAN) and Local Area Networks (LAN), traffic demands have shown different dynamics. At the same time, the emergence of end-to-end QoS concerns has made it desirable to apply network design and resource provisioning techniques that were considered more suited to backbone networks to these lower level networks. In such networks, the magnitudes of traffic demands are more appropriately modeled as some functions of time. The traffic grooming problem has been generalized into this arena, giving rise to *dynamic* traffic grooming.

The static traffic grooming problem can be conceptually decomposed into three sub-problems:

- The virtual topology design subproblem,
- The routing and wavelength assignment (RWA) subproblem
- The routing of traffic demands on the lightpaths, or grooming, subproblem

Figure 1 shows the layered nature of these subproblems. Briefly, the network physical topology of optical fibers is an input to the problem, as is the set of traffic demands to be satisfied. The networks designer must decide what set of lightpaths to implement in the network; this is called the virtual topology subproblem. Having decided the virtual topology, the designer must specify a physical route for a lightpath from each source to each destination and assign to each lightpath a wavelenght out of a given set, such that no more than one lightpath of a given wavelength traverses each link, and the wavelength assigned to each lightpath is the same on all physical links. This is the Routing and Wavelength Assignment (RWA) problem, which has been extensively discussed and studied in optical networking literature; see [3] and references thereof for a detailed discussion. Finally, the subwavelength traffic demands must be routed over the lightpaths formed, so that each traffic demand is carried by a sequence of lightpaths that form a path in the virtual topology which carries the traffic from its source to its destination. Traffic is transferred from one lightpath to the next in the sequence by OEO routing. Global minimization of OEO routing or OEO equipment required at network nodes is often the goal of static traffic grooming, as mentioned above.

The dynamic traffic grooming problem can be understood in terms of exactly the same subproblems. However, the objective of grooming must be seen in a new light. Unlike the static problem, in the dynamic traffic grooming problem the solutions to these subproblems need to satisfy time-varying traffic. Thus the solution itself must vary with time. At the least, the mapping of traffic demands to the virtual topology must change. Also, network designers can take the advantage offered by reconfigurable optical switches to dynamically adjust the virtual topology in response to traffic demand changes, in that case the RWA must also be readjusted to map the changed virtual topology onto the unchanging physical topology.

It is important to note that the focus of grooming traffic shifts as a consequence of the above. Reduction of OEO costs may continue to be an objective of traffic grooming. But the primary objective may now well be a minimization of the blocking behavior of the network; this is not particularly relevant in static traffic grooming because with good planning the entire traffic matrix is expected to be carried by the network, but making a similar 100% guarantee under statistically described dynamic traffic may be prohibitive in cost and not desirable. Similarly, the consideration of fairness is not relevant for the static problem, but may become an important one for the dynamic case.

Another change of focus relates to the complexity of the grooming solution. In static grooming, solution approaches of significant computational complexity may be practical, since such solutions are expected to be computed off-line, with a given estimate of traffic that is expected to be valid for a reasonably long time. For the dynamic case, the solution will be computed on-line, and re-computed over normal network time scales. Thus it is essential that the algorithms to compute new solutions be of low computational complexity. Similarly, an algorithm that can be computed in a distributed manner is likely to be of far more practical use in the dynamic context than one that requires a centralized approach; this distinction is less significant in the static case. Thus in various ways, the goal and priorities of grooming changes in the dynamic traffic context, and this is what we refer to as the changing role of traffic grooming. Finally, as the field evolves, it is likely to come to be perceived as a general class of network design problems where the cost component is largely concentrated into specialized network node equipment that will enter the mainstream in the future, such as optical drop-and-continue, wavelength converters, or OTDM switches.

The connection with the work in the Internet Engineering Task Force (IETF) in the GMPLS context is worth remarking upon. The original definition of Multi-Protocol Label Switching (MPLS) in the Networking Working Group of the IETF, building on earlier paradigms of tag switching and cut-through switching, was motivated by the need to reduce the forwarding burden on core routers. In label switching, an additional header is attached to Internet packets that carry information regarding flows to which each packet belongs. Once a flow, called a Label Switched Path (LSP) in MPLS, is set up, a Label Switching Router (LSR) in the path can forward packets bearing the label corresponding to the flow with much less processing than for a normal packet. In Generalized MPLS (GMPLS) [1, 2], time slot positions for TDM transport and wavelength channels for optical transport can also act as labels. It was soon realized by the networking community that label switch routing could also serve as an enabling mechanism for traffic engineering (TE), and flow-level QoS, because it allowed the identification of flows to routers. There has been significant recent work in defining extensions and signaling for the interaction of GMPLS and underlying networking layers, including SONET and other optical transports, and the communication of traffic engineering information between underlying networks and GMPLS [4–6].

However, these developments have focused (as appropriate for the role of the IETF) on enabling technology rather than design strategies. In keeping with the original guiding principles of the Internet, the network administrator is provided mechanisms to set up TE or QoS actions; but what actions are to be taken is left up to the administrator, who must look elsewhere for algorithms that provide policy or strategy decisions. To put it simply, all the mechanisms to set up LSPs is provided, but what LSPs to set up must be decided by the network administrator or operator. It is in this sense that research work such as traffic grooming provides a necessary complement to the development of enabling technology.

Because of the wide deployment of WDM networks, efficient operation under dynamic traffic is an area of practical interest to service providers. Efforts at different layers have already started in the arena of enabling technology to make the network friendly to dynamic traffic. At the lower layer, in the legacy Synchronous Optical Network (SONET) or the Synchronous Digital Hierarchy (SDH) networks, the hierarchical rates defined for multiplexing/demultiplexing make it inefficient to carry dynamic traffic requests. To overcome this intrinsic inefficiency, two mechanisms, Virtual Concatenation (VCAT) (as defined by the International Telecommunication Union in its recommendation [ITU-T G.707]) and the Link Capacity Adjustment Scheme (LCAS) (as defined in [ITU-T G.7042]) have been developed for Next Generation SONET. At the higher layer, part of the motivation to generalize MPLS to GMPLS has been to provide a uniform control plane to LSRs that operate at IP/MPLS level as well as network equipment that operate at fiber, wavelength and circuit level. Dynamic traffic grooming is thus a timely and emerging research area. Our focus in this survey is this research area, which is expected to provide algorithms that supply designs or policies for network operation.

While a significant number of studies have appeared recently on dynamic traffic grooming, there is as yet no single resource that provides a comprehensive introduction to the problem as well as to the literature. In this article, we hope to fill this void by providing an insight into the factors that must be considered in formulating a dynamic traffic grooming problem, and presenting a survey of the literature.

The rest of the article is organized as follows. We briefly discuss network node architectures for traffic grooming networks, because it is an important factor in dictating the goals of the network design problem. We provide discussion regarding the formulation of the dynamic traffic grooming problem either as a resource allocation problem or a policy design problem. This also allows us to present a classification of the literature, followed by a detailed literature survey according to our classification. We conclude with a few remarks on future directions.

NODE ARCHITECTURES

The extent to which subwavelength traffic components may be manipulated (and thus what grooming actions may be performed) is determined by the network equipment that are available at the nodes. Accordingly, in this section, we provide a brief overview of nodal capabilities. A more detailed discussion, with some discussion of future switch capabilities, may be found in [7].

Generally speaking, the traffic entering/leaving a node equipment can be described by a tuple (optical fiber, wavelength, time-slot). Thus, a “perfect” switching node would perform a complete permutation, i.e., the traffic from any fiber, any wavelength, and any time slot would be possible to switch to any other fiber, wavelength, time slot. However, due to considerations of cost and scalability, different node architectures are deployed in reality that have less than perfect switching capability. These impose different constraints on the grooming problem. We will show later how a mathematical formulation for the dynamic traffic grooming problem requires careful examination of the node architectures. A generic modeling of the constraints that applies to different architectures is also an interesting problem.

The basic conceptual building blocks of such switches can be broadly divided into optical components, which manipulate optical signals, and thus operate at the level of entire wavelength channels, and electronic or digital components, which are capable of manipulating individual bytes and packets as electronic signals, as in traditional routers and electronic computers. Optical networking switches will in general have some of each type of component, and can be characterized by the capabilities of each of these. When a number of signals are multiplexed into a carrier, multiplexers (MUX) and de-multiplexers (DEMUX) are required at the sender and receiver respectively. If an equipment has the capability to de-multiplex signals, then selectively switch some of them to another

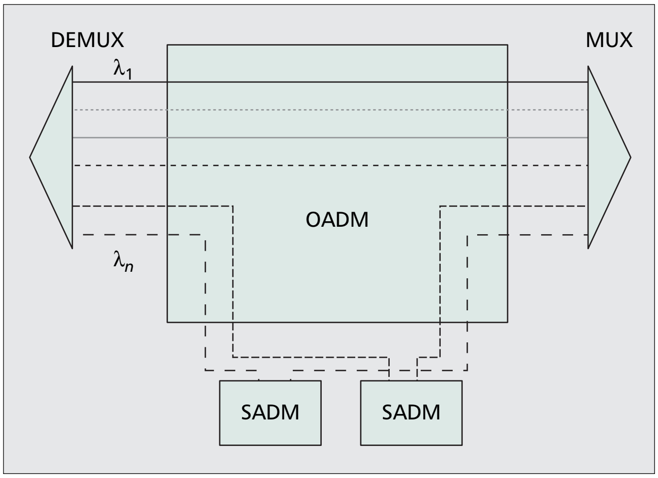

Figure 2. *An OADM architecture.*

switching equipment at the same node, while passing others through to a multiplexer for outgoing signals, it is called an Add- Drop-Multiplexer (ADM). Such an equipment performs only one decision for each de-multiplexed flow (whether to drop it or to pass it through). If, in addition, the equipment has the capability to choose which of several outgoing ports a signal is passed through to, it is called a Cross-connect (XC).

SONET/SDH ring networks were one of the first optical networking architectures to be used in practice, and continue to be important today. In SONET rings, only one optical channel on each fiber is used. Fibers are usually interconnected by SONET Add-Drop-Multiplexers (SADMs), which are digital equipment that have the capability to switch traffic at time-slot level. Thus the MUX/DEMUX refers to individual traffic streams time-division multiplexed in the optical signal. At a ring node, there is only one other node from which an incoming link exists, and only one other node to which an outgoing link exists. Thus Add-Drop functionality is all that is required. In SONET mesh networks, fibers are interconnected by Digital Cross-Connects (DXCs or DCSs), which, unlike ADMs, handle multiple input and output fiber ports. DXCs, which perform switching at time-slot level, can be characterized by p/q, where p represents the port bit rate and q represents the bit rate that is switched as an entity. For a comprehensive description of SONET/SDH, see [8].

For WDM networks, multiple wavelength channels are frequency multiplexed in each fiber links, and lower rate traffic streams are time division multiplexed in each wavelength channel. The digital equipment at the node can perform switching actions on the lower rate traffic streams by utilizing Synchronous Transport Signal (STS) in the optical signal. In WDM ring networks, an Add-Drop method as above can be used, but now Optical ADMs (OADMs) are used to selectively by-pass some wavelengths along the ring, while others are dropped into digital equipment, which may be SADMs. This forms the simplest node structure that can be used in optical grooming networks, and is shown in Fig. 2. The various wavelength channels frequency multiplexed in the fiber are represented by $\lambda_1 \ldots \lambda_n$. The by-passing of wavelength channels creates *lightpaths*, channels that are optically continuous over multiple physical fiber links. In Fig. 2, the first four wavelengths are by-passed in this fashion, whereas the last two are dropped (and added, at the output). It is possible to re-generate a lightpath signal on a different wavelength entirely by optical hardware (without converting the signal into the digital electronic plane), this is called wavelength conversion. However, such equipment is quite costly, and in many cases practical node architectures may not include such converters. Without wavelength conversion capability, lightpaths must obey the *wavelength continuity constraint*, i.e. a lightpath must be assigned the same wavelength on the fiber links it traverses. For each added/dropped wavelength, an SADM is dedicated to process the traffic the wavelength carries electronically. The number of SADMs at a node determine the number of wavelength channels for which traffic can be switched at the timeslot level, thus this number characterizes in part the switching power of the node. It is well recognized that the cost of transceivers is the main contributor to the network cost, therefore the number of SADMs available at an OADM is usually either the objective to minimize, or a constraint to which the optimization problem is subject. This problem is referred to as ADM constrained grooming in [9]. Furthermore, if the SADMs on the different wavelengths are isolated (as shown in Fig. 2), not only lightpaths but traffic components need to obey the wavelength-continuity constraint because the traffic dropped at a wavelength has to be sent onto the same wavelength in order to be forwarded to its destination, as in [9]. This constraint can be relaxed if a digital switching fabric is available such that the traffic added/dropped by SADMs can be reshuffled and re-injected into other SADMs, resulting in a more powerful switching node. Figure 3 shows an example of such a node, with optical MUX/DEMUX and OADM, and SADMs on each dropped wavelength connected by a DXC.

In contrast to OADMs, which usually have predetermined add/drop wavelengths, Reconfigurable OADMS (ROADMs) allow a network administrator or operator to dynamically select what wavelengths to drop or by-pass. The reconfigurability does not represent an increase in the power of the switch in terms of how much traffic can be switched, but introduces more flexibility. The number of maximum wavelengths that can be dropped characterizes the power of the switch, as well as the digital switching capability (as before). For a comparison of different ROADM architectures, refer to [10]. An example is shown in Fig. 4.

In all the above, the optical part of the switch is only an ADM, and the electronic part is an ADM or an XC. These can all be viewed as a special case of Optical Cross-Connects (OXCs), the most general class of grooming switches, which are widely expected to be deployed in realistic mesh topologies. In such switches, the optical ADM is replaced by an optical XC. Thus wavelength channels can not only be by-passed to form lightpaths, but these lightpaths can be switched to specific output ports. An OXC is similar to an ROADM, but can accommodate incoming fibers from multiple nodes, simi-

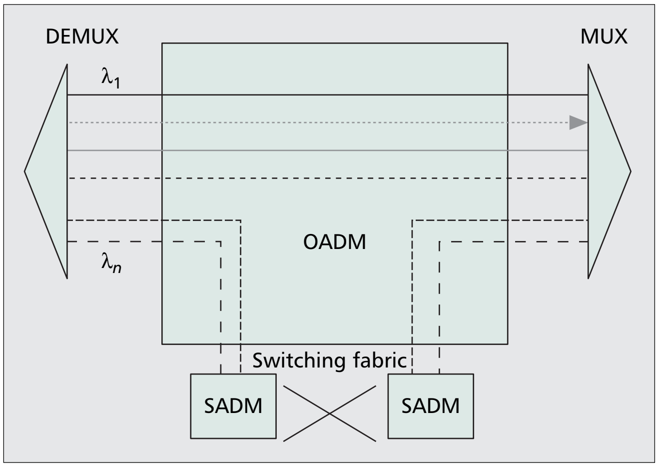

Figure 3. *An OADM architecture that allows cross-connect of local traffic.*

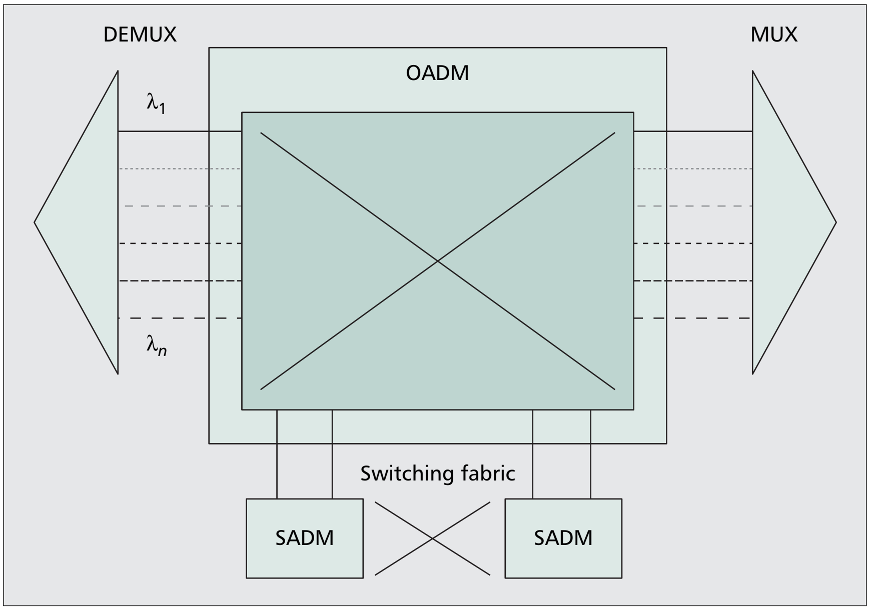

Figure 4. *An ROADM architecture.*

larly outgoing fibers to multiple nodes. Three broad classes of OXCs have been defined (refer to Telcordia's Optical Cross-connect Generic Requirements GR-3009-CORE):

- *Fiber switch cross-connect*: the entire signal carried by an incoming fiber is switched to an outgoing fiber, cannot perform different actions for different wavelength channels of timeslots.
- *Wavelength Selective Cross-connect*: can switch a subset of the wavelengths from an input fiber to an output fiber, obeying wavelength continuity constraint.
- *Wavelength Interchanging Cross-connect*: WSXC with wavelength conversion capability.

In addition, time slot multiplexing/demultiplexing and grooming can be performed by a DXC if it is incorporated in the node. Figure 5 shows an example of OXC that has grooming capability, with *m* input and *m* output fiber ports. (Usually, the number of input fiber ports is equal to the number of output fiber ports; however, in [11], the design of strictly non-blocking OXCs with different numbers of input and output fibers has been studied.) An OXC usually has two separate switching fabrics, the wavelength switching fabric that switches traffic at the wavelength level, and the grooming fabric that switches traffic at the time-slot level [12]. Since the grooming fabric can be viewed as a DXC, to avoid confusion, the cost is usually modeled in terms of the number of transceivers, instead of SADMs as in SONET ring networks. Note that both the transceiver and the SADM can be seen as terminating a lightpath into digital equipment; thus this cost measure can be generalized as the number of LTEs required.

Other node capabilities related to the ones described above are possible. A node intermediate in power between an ROADM and an OXC called Optical Add-Drop Switch (OADX) has also been defined and is commercially available; however, we do not discuss it here because from the grooming point of view such as node is equivalent either to an ROADM or an OXC. In [13], a node is modeled as trunk-switched and a generalized framework for analyzing *Trunk-Switched Networks* is addressed. The authors introduce the concepts of trunks and channels, whose definitions are node architecture dependent. Trunks can be viewed as forming a virtual layer, and an input channel can be switched to any output channel at a full-permutation node, as long as both channels are within the same trunk. For instance, without wavelength converters, a wavelength can be viewed as a trunk and if time-slot switching is permitted, a time-slot can be viewed as a channel. In [14], by the same authors, a network with heterogeneous node architecture is studied. However, this framework does not address the case of a node which combines different node architectures. For example, while the added/dropped wavelengths can interchange time slots through the switching fabric, an OADM has some bypassing wavelengths (trunks) in which time slots can not be switched.

As the above discussion shows, depending on the node architecture, a node can operate at the fiber, wavelength, or time-slot level, and at each level, it may have full or limited functionality. In addition, some variants are worth mentioning. For instance, to avoid the cost of full grooming DXCs, the grooming functionality can be separated into two levels, where the higher level is a coarse groomer that deals with high speed traffic streams and the lower level is a finer groomer that deals with low speed traffic streams. The authors of [15] consider such a situation, and remark that using the proposed mixed-groomer node architecture is beneficial in terms of reducing both the switching cost and the number of wavelengths required. In the node architecture introduced in [16], an extra waveband layer is inserted between the wavelength and the fiber layer. In [17], the authors describe a node architecture, Multicast- Capable Grooming Optical Cross-connect. Using the embedded strictly non-blocking splitter-and-delivery (SaD) switches, the proposed dynamic tree grooming algorithm can be supported. In [18], another Multicast-Capable Optical-Grooming Switch architecture is introduced. Instead of using SaD switches, it has two stages of optical switching. Multicast traffic leaving the first stage optical switch

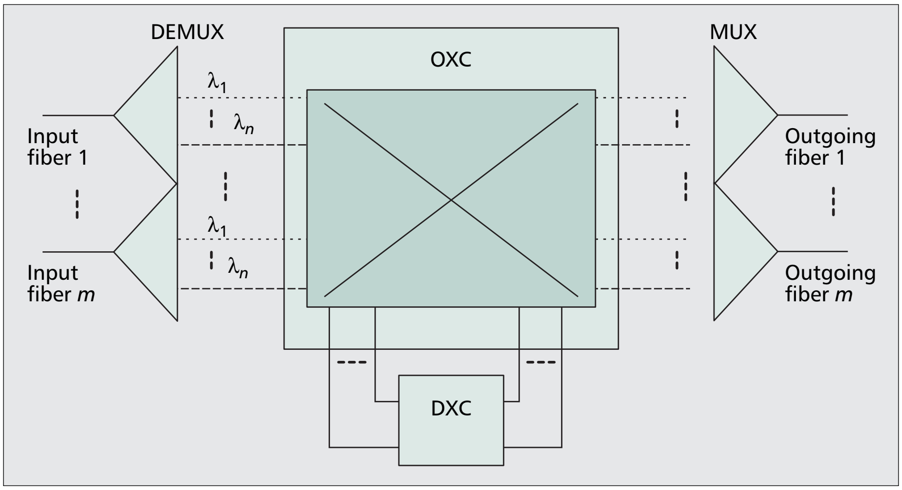

Figure 5. *An OXC architecture that has grooming capability.*

is sent to a splitter bank and then switched by the second stage optical switch.

THE DYNAMIC TRAFFIC GROOMING PROBLEM

In this section, we make some general observations to indicate the scope of problems dealt with in literature that we consider as coming under the umbrella of dynamic traffic grooming. Broadly, we include both problems that take an essentially dynamic approach to changing traffic and problems that convert this changing nature into a static design problem. However, the underlying problem should be motivated by the changing nature of traffic. Also, we consider the study to come under grooming only if the multiplexing of subwavelength traffic is considered to contribute to the cost model or constraints in some manner. We exclude literature from our scope if the only consequence of subwavelength traffic is seen to be the required multiplexing, because such studies are more appropriately considered to fall under the more established research areas of routing design and resource allocation with multiplexing. These considerations prompt us to consider out of scope studies such as [19], which is in effect static grooming study; or [20], which is more appropriately considered a restoration strategy design at the lightpath level. We use the concepts developed in this section to present a categorization of the literature and a detailed survey later.

DESIGN AND ANALYSIS PROBLEMS

In [21], we classified the dynamic traffic grooming problem into two broad categories: the *design problem* and the *analysis problem*. The distinction, while not an absolute, is a practically useful one in understanding approaches to the problem and categorizing them.

- The network *design* problem focuses on the state space; a time-varying one for the dynamic problem. Given a model of behavior of the network and some quantities of interest to optimize, the design problem attempts to find optimal settings of controllable parameters.
- The network *analysis* problem focuses on modeling the behavior. Given an a priori policy of network control under dynamic traffic events, such as arrival, departure, increment, decrement; the analysis problem attempts to develop a predictive model of some quantities of interest, under changing values of input parameters, such as arrival rates.

The two problems are complementary, because the design problem presupposes a model that allows computation of the goal under specific resource allocation and policy, and the analysis problem presupposes an existing policy and resource allocation under given traffic conditions. In the area of dynamic traffic grooming, analysis problems considered in literature generally address the blocking performance of the network under some given grooming policy, as experienced by arriving subwavelength traffic components. The design problems considered in literature show a larger variety both in the problems formulated as well as the approaches taken, and we discuss more of them in the rest of this section. At the end of this section, in Table 1, we use the distinction between design and analysis problems as our first categorization of literature on the dynamic traffic grooming problem. Later, we include surveys of both categories of literature.

QUANTITIES OF INTEREST IN DESIGN

We briefly list the basic quantities in terms of which the design problem is defined, with accompanying notation.

- Let N be the set of nodes and A be the set of directed fiber links in the physical topology graph. We assume that the physical topology does not change with time.
- Let S be the set of traffic demands denoted by the source-to-destination node pairs in the network; S may consist of all distinct ordered pair of nodes, but may also be a subset of it because some node pairs do not have traffic between them.
- Let $\Lambda_{|N|\times|S|} = [\lambda_n^s(t)]$ be the traffic matrix, where $\lambda_n^s(t)$ is the time varying traffic flow for the node-flow pair (n, s). Specifically, $\lambda_n^s(t)$ is λ_s, if at time t, the traffic demand s is sourced from node n, and has magnitude λ_s. Similarly, $\lambda_n^s(t)$ is $-\lambda_s$, if the traffic demand s is destined to node n, and 0 if n is neither the source not the destination of the traffic demand s. We suppose λ_s for every s is in units of a basic rate, and the capacity of a wavelength is C, in the same units.
- Let the number of wavelength channels available on each physical fiber link by W, wavelengths are numbered from 1 to W on each fiber.
- Let the matrix of the physical topology be $P_{|N|\times|A|} = [p_n^{(a)}]$, where $p_n^{(a)}$ is 1 if the fiber a is sourced from node n, –1 if it is destined to n, 0 otherwise.
- Let L be the set of lightpaths, and let $V_{|N|\times|L|\times W} = [v_{n,w}^{(l)}(t)]$ be the matrix of wavelength layered virtual topology, where $v_{n,w}^{(l)}(t)$ is 1 if at time t, lightpath l is sourced from node n and uses wavelength w, –1 if it is destined to n and uses wavelength w, 0 otherwise.
- Let $R_{|A|\times|L|\times W} = [r_{a,w}^{(l)}(t)]$ represent how the virtual topology is routed on the physical topology and assigned wavelengths, where $r_{a,w}^{(l)}(t)$ is 1 if lightpath l uses the wavelength w on fiber link a at time t, 0 otherwise.
- Let $G_{|L|\times|S|} = [g_l^{(s)}(t)]$ represent how the traffic demands are routed on the virtual topology, where $g_l^{(s)}(t)$ is λ_s if the traffic demand s traverses lightpath l at time t, 0 otherwise. This represents the case that traffic bifurcation is not allowed; additional variables can be introduced to represent bifurcated or diverse routing of traffic demands.

In general terms, the *input* to the dynamic traffic grooming problem are:

- The traffic demand matrix Λ, a function of time
- The resource availability (includes physical topology P, number of wavelength channels W, etc.), generally not varying with time
- The node architecture (limits to grooming capability, etc.), also generally not varying with time

The *output* of the dynamic traffic grooming problem are:

- The virtual topology V
- The routing and wavelength assignment V for the virtual topology on the physical topology P
- The routing G of the traffic demands on the lightpaths of the virtual topology

In general, all of the outputs are functions of time.

BASIC CONSTRAINTS

Constraints on the Node Architecture

- As we observed earlier, the total OEO processing capability of a node is directly constrained by the finite number of LTEs (SADMs or transceivers) at the node. This is expressed as:

$$\max\left(\sum_{l:v_{n,w}^{(l)}>0}\sum_{w} v_{n,w}^{(l)}(t),\ \sum_{l:v_{n,w}^{(l)}<0}\sum_{w} -v_{n,w}^{(l)}(t)\right) \le \mathrm{LTE}_n \quad \forall n \tag{1}$$

where LTEn is the number of LTEs available at node n.

Analysis (of Blocking Probability)	Virtual topology is assumed to be …	static, given	opaque [30, 31]
		dynamic, strategy given; call routing is …	single-hop [32]
			multi-hop [14, 27, 30, 31, 33–36]
	Specific modeling technique…	link loads assumed…	correlated [14, 27, 30, 31, 34, 37]
			uncorrelated [32, 33, 35, 36]
		traffic rate model	multi-rate Poisson [27, 31–35]
			single-rate Poisson [14, 30]
Design (Performance Optimization)	Traffic variation modeled as …	arrival departure model	Poisson model [30, 38]
			incremental [39]
			elastic [40]
		traffic matrix constraints	peak constraint [23, 41]
	Objective of design is …	blocking probability; network is …	non-rearrangable [23, 28, 42–56]
			wide sense non-blocking [26, 57]
			rearrangeable [26, 41, 44, 57, 58, 59]
		fairness [9, 27, 30, 38, 53]	
		OEO costs, metric is …	number of LTEs [22–24, 26, 42, 39, 55, 57, 60–63]
			number of wavelengths [22, 24, 26, 35, 57]
			amount of OEO processing [64]
	Virtual topology in solution is allowed to be …	static [65]	
		one per traffic pattern	
		sequence, schedule of virtual topologies [41]	

Table 1. *Variants of the dynamic grooming problem.*

- Earlier, we have shown that different node architectures may also result in different constraints on the feasible grooming solutions. For instance, the unavailability of wavelength converters imposes the wavelength continuity constraint in the RWA problem. Because the wavelength converters are expensive, most researchers assume that they are absent in the network. Consequently, lightpaths must obey the wavelength continuity constraint. That is;

$v_{n,w}^{(l)}(t)$ is 1 if at time t lightpath l is sourced from node n, –1 if at time t lightpath l is destined to node n, 0 otherwise.

Depending on the node architecture, there may be further constraints on the set of wavelengths a local transmitter can be tuned to. For example, practically, transmitters may be equipped with lasers with limited tunability (e.g., a recent OADM card provided by a major vendor can only be tuned to a band that has two predetermined wavelengths). However, if the wavelengths that are dropped/added are reconfigurable and completely selective, such a constraint is not required.

Constraints on the RWA Problem — To ensure correct RWA, we can use the following constraint or similar:

$$P_{|N|\times|A|}R_{|A|\times|L|\times W} = V_{|N|\times|L|\times W} \qquad (2)$$

To ensure one wavelength on a fiber is assigned to at most one lightpath, we can use:

$$\sum_{l} r_{a,w}^{(l)}(t) \le 1 \quad \forall a,w \qquad (3)$$

Constraints on the Traffic Routing — We use $V_{|N|\times|L|} = [v_n^{(l)}(t)]$ to denote the virtual topology at time t. $v_n^{(l)}(t)$ is 1 if the lightpath l is sourced from node n at time t, –1 if the lightpath l is destined to node n, 0 otherwise. Note that the virtual topology is the sum of the wavelength layered virtual topology, that is:

$$V_{|N|\times|L|}G_{|L|\times|S|} = \Lambda_{|N|\times|S|} \qquad (4)$$

The following constraint ensures the traffic demands are properly routed on the virtual topology.

$$V_{|N|\times|L|}G_{|L|\times|S|} = \Lambda_{|N|\times|S|} \quad (5)$$

To ensure the capacity of a lightpath is obeyed, we have:

$$\sum_{s} g_l^{(s)}(t) \le C \quad \forall l \quad (6)$$

STATIC AND DYNAMIC FORMULATIONS OF DESIGN

Static Formulation – Resource Allocation — While traffic demands change with time, the change may be partly or wholly *predictable*. As an extreme case, the nature of variation of traffic with time may be completely deterministic. If the value of the traffic demands at all times (over a period of interest) is known with certainty beforehand, the problem can be seen as some variation of a general *resource allocation* problem, and a static formulation of the problem is most appropriate.

In this model, the traffic is deterministically given over some period of interest, possibly as a sequence of traffic matrices, $\Lambda(t_0), \ldots, \Lambda(t_n)$. The period may be infinite, by specifying that the pattern of traffic matrices repeats; this is essentially a scheduling problem. This model is amenable to an Integer Linear Program (ILP) formulation [22]. One obvious approach to such a problem is to eliminate the effects of time-variation altogether by simply designing for the peak values each traffic component assumes in the entire set of matrices. However, as shown in [23, 24], using the traffic matrix formed by the peak rates may result in requiring an unnecessarily large amount of resources. The reason is the space-time nature of the dynamic traffic grooming problem, which is left out of consideration in this approach. The traffic matrix of peak rates is an overestimation of the traffic demands, because the dynamic nature of traffic spreads peak rates out along the time dimension. Thus this problem, while a static problem, is distinct from the static grooming problem.

Dynamic Formulation — Policy Design: On the other hand, unpredictability or uncertainty may be seen as an essential characteristic of the traffic model. In such cases, the dynamic nature of the problem needs to be explicit in the problem formulation. The problem must be seen as one of supplying a *policy design* for the network, that is an algorithm that the network control plane can employ to make decisions in response to traffic change events, with state and action space defined as follows.

State Space — Since traffic events can occur and network actions can be taken only at discrete points in time, we represent $\Lambda(t)$ as a discrete-time temporal process, Λ_i is the traffic matrix at time epoch t_i (a time epoch is defined as an instant at which a dynamic traffic event occurs). Then, each Λ_i is associated with a virtual topology V_i, a routing and wavelength assignment R_i, and a traffic routing G_i. The tuple $\{V_i, R_i, G_i\}$ is referred to as the grooming solution at time t_i. Then, the network state at time ti can be described by the tuple $\{\Lambda_i, V_i, R_i, G_i\}$.

Action Space — According to the layer it will affect, the actions taken by the network control algorithm can be classified as follows:

- Call Admission Control (CAC) actions, where two possible actions are **reject** and **accept**. If a traffic change is accepted, actions on other layers may follow. Note that while we use the term "call," the events may be more general ones than arrivals of entire subwavelength traffic demands; for example it may be an increment or decrement to the magnitude of a traffic connection already established. However, the network action must still start with a decision regarding whether to accept or reject the increment.
- Network layer routing actions. Once a change is accepted, the changed traffic will be either routed on the existing virtual topology, or it will trigger virtual layer actions. The actual route of the subwavelength call on the virtual topology must also be determined according to some policy. When the change is in the nature of a traffic decrease, network layer action may also be triggered to rearrange the routing of remaining traffic, see below.
- Virtual layer setup, teardown, or routing actions. To route the changed traffic component, new lightpaths may be set up. These may be either a direct lightpath, or a combination of new lightpaths, which may be further utilized in conjunction with existing lightpaths to route the changed traffic component. For new lightpaths, routing and wavelength assignment is performed. Similarly when traffic decreases, lightpaths may be also torn down in response.
- Re-routing Actions. Furthermore, if disruption of existing traffic is allowed, the actions may include rerouting (or even terminating) some existing traffic. Existing subwavelength traffic may be rerouted on the virtual topology, or existing lightpaths may be rerouted on the physical topology.

For each action, $\{V_i, R_i, G_i\}$ will change to $\{V_j, R_j, G_j\}$. The goal of the policy will be always to maximize some reward function, akin to the objective function for a static formulation; we discuss some possible goals later in this section.

Referring back to our discussion regarding Fig. 1, we see that the physical topology at the lowest layer does not change with time, and the highest layer, the traffic demands to be carried, do change with time. Thus dynamic traffic grooming strategies can be seen as the algorithms executed by the network to perform a time-varying mapping of the traffic onto the network resources, using the routing, wavelength assignment, and grooming, to satisfy the demands and satisfy some goal of network operation such as operating cost minimization or maximization of utilization.

MODELS OF NON-DETERMINISTIC TRAFFIC VARIATION

For the dynamic formulation, traffic variations are not wholly predictable, but the time-variation of traffic may nevertheless be modeled or characterized to some extent. Different models can be designed to reflect realistic network conditions, we list a few below.

- $\Lambda(t)$ is a Poisson process, and the model is simply one of subwavelength traffic component arrival/departure. In the general context of dynamic traffic grooming, it is reasonable to assume that $|\Lambda(t) - \Lambda(t + \Delta t)|$ is small for a short time period Δt, which motivates this model.
- Traffic demands are preferred to be serviced within time windows [25]. This is a generalization of the simple arrival-departure model. Instead of each traffic component requiring to be serviced at the instant (or as soon after as possible) that it arrives, every traffic component specifies a window of time within which the traffic component must be carried. The arrival process may again be Poisson, or some other process.
- Traffic demands are restricted by specified bounds. Such bounds may be provided by the traffic components themselves, or they may be imposed by the available resources. For example, the number of SADMs available at the node (referred to as t-allowable traffic in [23]). Let SADM_n be the number of SADMs at node n, then the traffic matrices must satisfy:

$$\max\left(\sum_{s:\lambda_n^{(s)}>0} \lambda_n^{(s)}(t), \sum_{s:\lambda_n^{(s)}<0} -\lambda_n^{(s)}(t)\right) \le \mathrm{SADM}_n \cdot \mathrm{C} \quad \forall n$$

- Traffic components change in magnitude over time in *increments* and *decrements*. The process by which increments and decrements occur may be Poisson or some other.
- Entire traffic matrices are specified as in the deterministic model, but the time epochs t_i are not deterministic, and varies according to some random process.

DESIGN GOALS

The goal of either resource allocation or policy design is to minimize some measure of cost in provisioning and operating the network, and/or to maximize the benefit from the network. This can be embedded as cost function(s) in a static formulation, and reward function(s) in a decision formulation. In the literature, different goals have been articulated, some representative ones include:

- Minimize the network cost; these are more suitable for the static, resource allocation, view:
  - –Number of ports at network nodes (converters, LTEs, wavelengths)
  - –Amount of OEO processing
- Maximize the revenue by providing better service or better utilization of the network resource; more appropriate for the dynamic, policy design, view:
  - –Minimize the blocking probability
  - –Minimize the provisioning time (time to setup a connection for an arrival, traffic delay, etc.)
  - –Minimize the disruption to traffic already being carried
  - –Minimize the unfairness (e.g., traffic demands having different bandwidth requests should have approximately the same blocking probability)

These goals are usually correlated in a way that makes it impossible for them to be optimized simultaneously. Therefore, some kind of trade-off or preference must be considered. For example, in [26], the network architectures for WDM SONET rings that have the minimal SADM cost are studied, but subject to a limited number of wavelengths. In [22], an MILP for the dynamic traffic grooming problem with the objective of minimizing the SADM cost is solved by two phases, where, in the first phase, the number of wavelengths is minimized. In [27], the authors propose a connection admission control mechanism that provides good fairness without over-penalizing the overall blocking probability. In [23, 28], the objective is to design networks with the minimal SADM costs while keeping the existing traffic undisrupted (non-blocking in the strict sense).

SURVEY OF LITERATURE

LITERATURE CLASSIFICATION

Based on the observations we made in the last section, we present an organized view of the literature on the dynamic traffic grooming problem in Table 1. Because all the categories are not orthogonal, several papers appear in multiple places in this table. Thus this table should be thought of as an organization, even more than a categorization.

Moreover, some studies address more than one category of problem. For example, consider the variants of blocking probability that are considered in the literature. The blocking characteristic of a network can be classified as strict-sense non-blocking, wide-sense non-blocking and rearrangeable non-blocking (e.g., in [23]). If the network resources can guarantee strict-sense non-blocking, then all the new arrivals will be satisfied, and the policy design problem may not be addressed since it is trivial. However, if network cost considerations dictate accepting lesser blocking performances, to design a wide-sense non-blocking or rearrangeable non-blocking network, both the problems of resource design and policy design (to route new arrivals) are likely to be addressed.

In the remainder of this section, we go on to survey the literature in more detail. Table 2 contains the list of all papers surveyed below, with short descriptions that, combined with Table 1, indicate where the detailed survey of each paper appears below. A fuller description of some of this literature may be found in [29].

ANALYSIS STUDIES

As we have discussed in the previous sections, the resource and policy design problems are in essence optimization problems. In order to evaluate the performance (usually, the blocking probability) of a design, practitioners often resort to massive simulations. As simulation results are generally specific to the input (arrival and departure rates, etc.) and time consuming, analytical modeling is not only interesting in its own right but practically meaningful. In literature, the metric of greatest interest is the blocking probability, i.e., the ratio of the number of accepted arrivals to the total number of arrivals. In order to accept an arrival, the subproblems described in Fig. 1 should be solved. We distinguish two cases, the single-hop case and the multi-hop case (referred to as dedicated-wavelength TDM and shared-wavelength TDM in [13]). In the former case, a new arrival is accepted if it can be routed on a single lightpath (either an existing one or a new one to be established) from source to destination. In the latter case, the arrival is allowed to traverse multiple lightpaths, which could be a combination of existing lightpaths and newly established lightpaths. In addition, some routing and wavelength assignment algorithms must be assumed, e.g., the shortest path routing and random wavelength assignment algorithms considered in [13, 14]. In queuing networks, we also distinguish single-rate and multi-rate requests. In the single-rate model, all traffic demands have the same magnitude. The model simplifies the analysis significantly. However, in grooming networks, the multi-rate model may be more realistic because traffic demands are usually subwavelength, thus in units of some basic rates (say, OC-3).

Another difficulty comes from the traffic model. It is well known that the Poisson model fails to capture the self-similarity of the traffic pattern in networks. In addition, in grooming networks, traffic demands usually traverse multiple physical/logical hops. Therefore, the link load correlation becomes an important issue.

All these challenges and difficulties make the exact queuing analysis intractable. Accordingly, researchers have made different assumptions and simplifications. In the following section, we survey related works in this field.

Multihop Models with Correlation — In this section we describe those studies which make the more general assumption that end-to-end traffic components may be carried either on a single lightpath from source to destination, or on a sequence of lightpath. Additionally, these studies attempt to represent the correlation between the link loads in some manner.

As previously mentioned, in [13], Srinivasan *et al.* had pre-

[40]	Traffic Modeling. Elasticity of IP traffic impacts grooming algorithms.
[48]	Using an auxiliary graph with variable edge weights and grooming policies to achieve multiple goals.
[27]	Call Admission Control algorithm dealing with capacity fairness.
[52]	Various grooming policies combined with path inflation control.
[54]	Extend path inflation control to provide differentiated services.
[25]	A sliding window traffic model that introduces the scheduling problem to dynamic traffic grooming.
[18]	Traffic grooming for multicast traffic.
[50]	An auxiliary graph approach with low time complexity.
[51]	A two-phase dynamic grooming algorithm using simplified auxiliary graphs.
[56]	A comprehensive study of routing algorithms in traffic grooming networks.
[26]	Comparison of typical ring architectures that guarantee non-blocking.
[23]	Minimization of the number of ADMs for t-allowable traffic.
[42]	Heuristics to solve the design problem in rings with given traffic matrices.
[28]	A genetic algorithm for strictly non-blocking grooming in unidirectional rings.
[24]	Design in mesh network using traffic time-varying state information.
[35]	An ILP formulation for mesh networks taking the blocking probability into consideration.
[16]	A mathematical model for routing and grooming with scheduled lightpath demands.
[60]	Extension of [16] by taking subwavelength traffic (scheduled electrical demand) into consideration.
[61]	The placement of grooming nodes formulated as a dominating set problem.
[43]	An auxiliary graph approach with link-bundling.
[44]	Rerouting algorithms for varying traffic demands.
[49]	Traffic grooming with a drop-and-continue node architecture.
[17]	An auxiliary graph approach that supports dynamic unicast traffic.
[45]	An auxiliary graph approach that introduces the virtual graph and layered graph.
[46]	Routing, wavelength assignment and fiber selection algorithms in multifiber WDM networks.
[41]	Dynamic traffic grooming with reconfiguration algorithms.
[62]	Making grooming decision by monitoring the link performance.
[59]	Reconfiguration of virtual-topology by monitoring the link load.
[65]	A layered dynamic routing strategy in GMPLS networks.
[30]	A Markov Decision Process model for dynamic wavelength allocation in 2-hop tandem networks.
[38]	Call Admission Control for subwavelength traffic demands formulated as Markov Decision Process Problems.
[53]	Auxiliary graph with fairness grooming policies.
[32]	Blocking probability in single-hop traffic grooming mesh networks.
[33]	Blocking probability in multi-hop traffic grooming mesh networks.
[31]	Blocking probability in tandem networks, an exact solution with multi-rate arrivals.

Table 2. *Literature summarization.*

sented a framework for analyzing the performance of Time-Space Switched optical networks. In [14], this framework is applied to networks with heterogeneous node architectures. Assuming a single rate model, the blocking probability for a path is computed recursively from a two-hop path model. The authors assume *Markovian correlation*, i.e., the traffic on a link only depends on its previous link. In [34], the authors extend the work to the multi-rate case.

Washington *et al.* also study the mulithop model with correlations [31]. If they consider the blocking probability on tandem networks, i.e., a unidirectional path virtual topology. The authors consider the multi-rate arrival model on existing lightpaths. A path network is first decomposed into subsystems consisting of two adjacent nodes and analyzed exactly by a modification of Courtois' method. The first step of the Courtois' method that requires solving a system of equations is replaced by solving a multi-rate model for the exact conditional steady-state probabilities. After that, the link load correlation is considered by proposing an iterative method.

In [37], two types of grooming networks are distinguished, the constrained grooming networks where each node of the network has wavelength switching and subwavelength traffic grooming capability, and the sparse grooming networks where some nodes have limited grooming capability while others have none. The authors start with a simple two-hop single-wavelength capacity-correlated system with multi-rate traffic requests. Using these, a more complex and realistic multi-hop model is solved. The application of this model in performance analysis of general networks is also demonstrated. Because the capacity correlation model is specified for single wavelength systems, routing and wavelength assignment is not addressed in the article.

Uncorrelated Models — In some studies, a simplifying assumption of uncorrelated link loads is made. Xin *et al.* study the blocking performance analysis problem on traffic grooming in single hop mesh networks using such an uncorrelated model [32]. A closed-form formula is derived by some simplifications. For example, a single-wavelength link (SWL) blocking model is introduced and the multi-rate arrivals are converted into bulk arrivals and approximated departures. The authors also assume that overflow traffic is Poisson. Then a reduced load model is used to compute the end-to-end blocking probability.

By the same authors, the work in [33] is an extension of [32] that takes multi-hop routing into consideration. The authors propose a simple admission algorithm at a source node for each incoming traffic demand. A routing strategy is given such that the SWL model introduced in [32] can be extended to include multi-hop traffic arrivals. Instead of the sequential overflow model, a random selection of two-hop paths for the overflow multi-hop traffic demand is performed.

Yao *et al.* [36] also study the multi-hop case. Their model is as follows. For a given source-destination pair, some link-disjoint alternate paths are pre-determined and the s-d pair is blocked if all alternate paths are unable to carry it. On an alternate path, traffic can be electronically processed at some grooming nodes. To select grooming nodes, the authors introduce the load sharing policy, which tries the route without intermediate grooming nodes first and randomly select a candidate route if the direct one fails. Accordingly a path is blocked if all candidate routes are unable to satisfy it and respectively, a route is blocked if any of the lightpaths it consists are unable to satisfy it. Assuming the wavelength conversion capability is absent, a lightpath can be carried if there is an available single wavelength path (i.e., an available wavelength on all the links along the lightpath). The availability of a single wavelength path is in turn decided by the availability of the set of single wavelength links it consists, i.e., the existence of a set of common channels (time slots) that can satisfy the amount of capacity the s-d pair requires. Some restrictive assumptions are made in this study. First, the single wavelength links that make up a single wavelength path are assumed to be uncorrelated. Similarly, the lightpaths in a route are assumed to be uncorrelated. Finally, the overflow traffic is assumed to be Poisson.

Other Models — The study in [40] deals with the traffic models in traffic grooming networks. The aim of the article is to investigate how traffic elasticity, the reactivity of traffic with respect to the changing environment (load, e.g.), impacts grooming. The authors argue that even in core networks, the traffic is elastic in nature. Therefore, it is inappropriate to model them as the traditional circuit switched traffic. Specifically, two traffic grooming policies, one preferentially using existing lightpaths and the other preferentially setting up new lightpaths, are studied under two traffic models that have some feature of elastic traffic. The first model, which is less complex, captures the decrease of throughput of traffic when there is a congestion. The more complex model captures the fact that the more congested the network, the longer flows remain in the network. Different combinations of the traffic models and the grooming policies are simulated and compared. The simulation results show that the interaction between the IP and optical layer gives rise to some complex behaviors, which suggests that neither grooming policies are suited for the management of an IP over WDM grooming network, because they do not take the interaction between the IP and optical layer into consideration.

As we have mentioned earlier, [25] studies the "sliding scheduled traffic model". Specifically, a traffic demand is given by a tuple $\{s, t, n, l, r, \tau, p\}$, where s and t are the source and destination respectively, n is the bandwidth requirement, l and r are the starting and ending time respectively, and τ is the duration of the request; p is a binary parameter representing the priority of the demand. The traffic demand is required to be scheduled within the time window l to r (i.e., it should start between the time interval l to $r - \tau$); otherwise, it needs to be rearranged. Then the traffic grooming problem conceptually consists of two parts, the scheduling part and the grooming part. The scheduling part decides the starting time for each traffic demand in a manner such that the number of overlapping demand pairs in time is minimized. The grooming part then performs a time window based grooming algorithm. A space-time traffic grooming algorithm is proposed and compared with a tabu search algorithm that uses fixed alternate routing. The authors claim that the former algorithm outperforms the latter one in terms of the number of lightpaths.

DESIGN STUDIES

Studies of the design problem usually contribute both in formulating the problem with a particular objective, and then obtaining a solution to it. Therefore, two major concerns are how accurate the formulation is and how amenable it is to a solution. In dynamic traffic grooming networks, one important challenge that impacts the accuracy of the model is how to model traffic variations. As we have seen in Table 1, different traffic models have been proposed. We have already mentioned that the problem can be formulated as an ILP when the traffic model is deterministic, or specifies that the traffic changes entirely to a new traffic matrix while the network is running [58].

Obtaining a solution corresponding to the formulation also poses a separate challenge. Since the general static traffic grooming problem is NP-Complete [63, 64], obviously the general dynamic traffic grooming problem with the static formulation, which has significantly more time dependant variables is also NP-Hard. It has been previously shown that the static problem may be even inapproximable [64]. Because of this, most research focuses on heuristic approaches.

Objective of Minimizing Blocking Characteristics — As we have discussed earlier, it is generally very hard (if not impossible) to find a closed-form solution to the blocking probability in grooming networks. Therefore, many researchers propose heuristic traffic grooming algorithms and compare their performance in terms of blocking probability. We distinguish different kinds of network characteristics desired in terms of blockings. In non-rearrangeable networks, the algorithms can not disrupt the existing traffic. In rearrangeable networks, the existing traffic and/or virtual topology can be reconfigured or rerouted, which generally serves to lower the blocking.

Non-rearrangable Approaches — Because of the heuristic nature of grooming algorithms, some simple policies (or rules of thumb) may provide us some insight into the whole problem. When there is a new arrival, two simple and straightforward policies are

- Setting up a new lightpath
- Using the existing virtual topology

In [40], as we discussed, these two policies are studied under two traffic models that have some feature of elastic traffic. The above grooming policies are classified as operation oriented policies in [52], which deals with the operations that will be performed to accommodate an arrival. Heuristic algorithms are advanced to decide between establishing a new lightpath or routing on the existing IP topology for an arriving LSP request. The decision is based on monitoring the current level of congestion in the network, because routing on the IP topology may increase congestion, but depending solely on new lightpaths will exhaust network resources quickly. In [54], the same authors extend the same idea to provide differentiated services based on the priority. High priority LSP requests should have lower blocking probability than the low priority requests. Low priority requests will be blocked if no lightpath can be set up due to the wavelength or transceiver limit. However, high priority requests will be routed on the IP/MPLS layer. The algorithm proposed is further modified by introducing the Average Path Inflation Index , which takes the holding time of LSP requests into account. The authors claim this algorithm can be extended to handle more than two priority classes.

Sabella *et al.* propose a strategy for dynamic routing in GMPLS networks [65]. The proposed strategy has two phases. First, an IP/MPLS topology is considered, where there is an MPLS link between two nodes if and only if there is at least one lightpath interconnecting them. Based on this topology, a proposed routing algorithm extends the least resistance routing weight method [47] to the multi-layer GMPLS paradigm, where subwavelength LSPs are routed. The second phase is the grooming phase, where the LSP is groomed into lightpaths. Two policies, the packing policy that prefers the most loaded lightpath and the spreading policy that prefers the least loaded lightpath, are addressed.

In [28], the authors use a genetic algorithm to find a grooming solution in a strictly non-blocking manner for all-to-all traffic demands. New traffic demands are satisfied without re-routing and reconfiguration. To realize the strictly non-blocking property, the chromosome is decoded by a first fit approach incorporated with a local greedy improvement algorithm.

Auxiliary Graph Algorithms — Several design studies to minimize blocking performance are distinguished by their use of a common methodology, and we discuss them separately in this section. These studies use an auxiliary graph of some sort constructed from the network graph, where information regarding other constraints or goals of the problem are embedded in the auxiliary graph. This approach takes the advantage of the flexibility of an auxiliary graph to use simple routing algorithms. The overall design algorithm can thus be expected to have low complexity and be suitable for on-line use, but can take cross-layer information and heterogeneous node architectures into consideration. Different studies propose different auxiliary graph constructions. Many of these studies are inspired by [48].

The study in [48] creates an auxiliary graph that has an access layer, a lightpath layer and W wavelengths layers, where W is the number of wavelengths on a fiber. Each layer has an input port and an output port. Different edges representing different node capabilities are inserted between ports. An edge has a property tuple that states its capacity and weight, which reflects the cost of each network element (transceiver, wavelength-link, wavelength converter, etc.), and/or a certain grooming policy. Different grooming policies are achieved by applying different weight-assignment functions to the auxiliary graph, which reflect various objectives. In [12], Zhu *et al.* study a more specific resource provisioning problem where network nodes have different grooming architectures. Without wavelength converters, the graph model proposed in [48] is simplified to consist of four layers, the access layer, the mux layer, the grooming layer and the wavelength layer. By splitting the lightpath layer in [48] into the mux and grooming layers, the model is able to support different types of lightpaths distinguished by the source and/or destination node grooming capabilities. Using this model, the authors illustrate how different traffic engineering optimization goals can be achieved through different grooming policies.

The auxiliary graph constructed in [43] has two layers, the virtual topology layer and the physical topology layer. An improvement to the previous work is the introduction of the link bundling (or more accurately wavelength bundling). In particular, following constraints are taken into consideration: the transceiver constraint and the generalized wavelength continuity constraint, which allows nodes equipped with different kinds of conversion capability. The Link Bundled Auxiliary Graph simplifies the auxiliary graph representation in [48] by aggregating at most the number of wavelengths available on a link into one arc. Based on the graph, an algorithm is proposed to find a feasible path and a feasible wavelength assignment. As multiple feasible paths may exist, grooming policies are introduced to select the preferred one.

In [49], Farahmand *et al.* propose the Drop-and-Continue node architecture, which, in addition to setting up some new lightpaths and/or utilizing existing lightpaths, allows two other operations, namely, drop-and-continue and lightpath extension. These two operations can reduce the network cost, especially for multi-cast networks where we have one source node and many receiving nodes. The auxiliary graph constructed has a dedicated layer for each wavelength and different edges describing existing lightpaths, potential lightpaths, potential extended lightpath and sub-lightpath. By assigning them different weights using different grooming policies that are essentially the same as those in [48], a shortest path algorithm is used to find the best solution. Note that without the intermediate dropping and extension capability, this algorithm becomes identical to that of [48].

In [17], the same authors use a similar approach, but specifically for unicast traffic. A difference of the constructions between this article and [49] is the introduction of the grooming layer. Based on the auxiliary graph, a dynamic tree grooming algorithm, which has the weight assignment strategy (referred to as routing polices) as a sub-routine, is proposed. As in [49], the edges are assigned weights by different policies. Accordingly, the shortest path algorithm is used by the algorithm to setup a connection for an arrival. Specifically, the connection is set up either by establishing a new tree of drop-and-continue nodes along the vertices on the optical hop or extending an existing tree to cover the remaining vertices.

In [45], Two auxiliary graphs, namely the virtual graph and the layered graph, are introduced. In a virtual graph, the edges (so called partially available edges) represent the existing lightpaths that have spare capacity. The edges in a layered graph are fully available edges. Upon these two graphs, a two-layered routing algorithm is proposed, which tries to route a traffic demand on the virtual graph first, then tries the layered graph if the first step fails. Then, a single layered routing algorithm based on an integrated graph, which does not distinguish partially available edges and fully available edges, is proposed. The shortcoming of this algorithm is that using the shortest path algorithm on an integrated graph may result in a route that uses more new transceivers. A third algorithm is proposed to combine the advantages of the first two. The algorithms are compared in terms of the blocking probability and the joint routing algorithm outperforms the others irrespective of whether the number of transceivers is small or large.

In [50], Ho and Lee argue that, the algorithms proposed in [48] can be time-consuming in large scale mesh networks. A remedy is proposed by considering only part of the whole network when auxiliary graphs are constructed. Specifically, when a traffic demand arrives, instead of constructing an auxiliary graph with n nodes, where n is the number of nodes in the network, m candidates that are in the physical shortest path of the traffic demand are evaluated. If no lightpath can be found, neighbor nodes of the candidates are included into the consideration. This procedure can be repeated until a lightpath is found or resources are exhausted. In [51], based on the same idea, the authors propose a dynamic traffic grooming algorithm. In the first phase, to reduce the complexity of constructing an auxiliary graph of the entire network, a reachability graph that includes all the possible logical paths between the source and the destination is constructed. Based on the graph, the second phase is to find the optimal route by a cost-constraint algorithm, where the cost of interest is the sum of the cost of grooming fabrics and the penalty paid for wasted wavelength bandwidth.

Wide-Sense Non-blocking Studies — While all such studies aim at minimizing the blocking probability, in general the result is some low value of blocking. A few studies are able to propose approaches that result in a completely non-blocking network under specific conditions, and we discuss them separately here. The non-blocking achieved is *wide-sense*, that is the algorithm provided must be used exclusively for routing calls in that network, otherwise blocking may appear.

In [26], Sasaki and Gerstel study the dynamic traffic grooming problem for some typical WDM SONET ring architectures that guarantee no blocking. The primary network cost is the number of SADMs while the secondary concern is the number of wavelengths. For unidirectional path switched ring networks with limited number of wavelengths, a lower bound is derived by assuming the traffic is allowed to be cross-connected at every node. Given this lower bound, a single-hub architecture that guarantees wide-sense non-blocking, as well as a node grouped architecture designed for static traffic, are compared. For the wavelength limited case, the single-hub architecture and an incremental architecture are compared. The incremental architecture is a simplified version of the incremental network described in [57], where around the ring, nodes alternate between having the maximum and minimum number of ADMs. It shows that the incremental architecture is rearrangeably non-blocking and also wide-sense non-blocking for incremental traffic [57]. For two-fiber bidirectional line switched ring networks with unlimited number of wavelengths, the single-hub architecture is wide-sense non-blocking and it leads to a lowering of the bandwidth requirements because traffic may be routed on either direction of the ring. For the bidirectional wavelength limited case, the double-hub network is rearrangeably non-blocking [57], and the SADM cost is close to that of the single-hub network.

Rearrangeable Approaches — The disruption caused by rearrangement of traffic being currently carried by the network may be an acceptable tradeoff for the reduced blocking that is usually obtained by using the added flexibility of rearrangement. In such studies, one main concern is when and how the network should be reconfigured to effect the rearrangement, and when rearrangement should not be attempted.

Kandula and Sasaki study the dynamic traffic grooming problem with rearrangement on ring networks [41]. The authors provide a reconfiguration algorithm, called bridge-and-roll, such that the number of LTEs is reduced while keeping the network as bandwidth efficient as a fully opaque network. Putting different constraints on the resources, some interesting traffic models are introduced to illustrate the algorithm. In addition, to reduce the cost of traffic disruption, bounds are provided in terms of the number of reconfigurations.

In [59], Gencata and Mukherjee also study the reconfiguration problem. The traffic is assumed to fluctuate slowly compared to the observation period. In each observation period, the network load is monitored and compared with a high and a low watermark, which indicate if the link is under-utilized or congested. In an observation period, exactly one action, setting up a new lightpath or tearing down an lightpath, can take place. The duration of the observation period is adjustable to make a trade-off between efficiency and traffic disruption. If some links are congested, one new lightpath is setup in the observation period. If some links are under-utilized, one lightpath is torn down. The authors first formulate the problem as an MILP problem, with a goal to minimize the maximum load, with constraints that ensure the correct action is triggered and the virtual topology changes correspondingly. Then, the authors propose a heuristic adaptation algorithm. If some links are congested, the algorithm simply picks the link that has the maximum load and the maximum traffic component that traverses the link, then sets up a new lightpath for the selected traffic component. The authors use actual observed traffic traces for validation.

Based on a two-layer architecture, the authors of [15] propose an algorithm that allows rerouting existing traffic. It also allows segmented backup where multiple backup paths are allowed to share the same bandwidth. Traffic requests are multi-rate requests, and may or may not require protection. Therefore, to satisfy a new arrival with protection requirement, both the primary and backup routes need to be set up. In case rerouting existing traffic is necessary to accommodate a new arrival, end-to-end backup routes are considered first, in order to minimize disruption. If no route that is link-disjoint with the current primary and backup routes is found, all backup routes (end-to-end or segmented) are considered. The "best" route for a backup route is found if rerouting the backup on this route can satisfy the new arrival. Finally, existing traffic without protection requirements or with end-to-end backups are considered for dropping or rerouting.

The authors of [44] also study rerouting. When a traffic request arrives, rerouting is performed only if the existing routing fails to accommodate the request. The rerouting can be at lightpath level or connection level. The former changes the virtual topology while the latter only changes the routing of traffic on it. Both approaches have advantages and disadvantages. Lightpath rerouting may have lower time complexity because the input is the set of lightpaths, which are much fewer than the traffic requests. However, it is subject to a longer time of disruption because of the laser re-tuning time involved. Connection rerouting, although more complicated, provides a finer granularity of adjustment. Practically, a combination of both approaches may be more appropriate. Based on these two approaches at different layers, two algorithms are proposed. The first algorithm initially finds the set of critical wavelength of a path (the set of wavelengths that are used on only one link along the path), then the lightpath using this critical wavelength is rerouted such that a traffic request can traverse the path. Similarly, the latter algorithm finds the set of critical connections for a path and a connection request and reroutes the critical connection so that the new request can be satisfied.

Objective of Maximizing Fairness — Another objective of interest in traffic grooming networks is the fairness as we mentioned earlier. The main concern is that, traffic with lower bandwidth requirements should not starve traffic with higher bandwidth requirements, i.e., traffic with different bandwidth requirements should experience similar blocking performances. Otherwise a user transmitting a big file may have to choose to request a low bandwidth and take a longer time, in order to avoid blocking. Indeed, fairness is one of the important metrics of QOS, which is generally implemented by the Call Admission Control. While CAC comes under the general area of grooming policy design, it is a distinct area which has received significant attention and it is worth mentioning separately. As one of the major functionalities that the control plane needs to implement, CAC has been extensively studied in signaling-based networks (e.g., ATM), where a call is accepted or rejected with respect to a pre-established agreement between the user and the service provider or the resource availability. In the context of optical grooming networks, we expect that some "old" concepts (e.g., QOS) will be re-examined by taking the virtual layer into consideration. As we have mentioned, when a new call arrives, the basic actions to take are *accept* and *reject*. Without CAC, a call will be rejected only if the available resources are unable to accommodate it. However, in a network with service differentiations, this simple strategy may not lead to an optimal overall utilization/revenue.

In [27], a CAC algorithm is proposed to deal with the capacity fairness, which is achieved when the blocking probability of m calls of line-speed n is equal to the blocking probability of n calls of line-speed m, and this is true for every pair m, n of line-speed. The overall blocking probability is defined as the blocking probability per unit line-speed of the call requests. The fairness ratio F_r is defined as the ratio of the estimated blocking probabilities of calls of lowest and highest line-speeds. Therefore, the goal of the CAC algorithm is to make F_r as close to 1 as possible while keeping the overall blocking probability acceptable.

Mosharaf *et al.* study the CAC problem from the wavelength provisioning aspect in [30]. A simple 2-hop tandem network with three classes of wavelength requests, requests traversing the first hop only, requests traversing the second hop only and requests traversing both hops, is considered. This problem is formulated as a Markov Decision Process problem. When a wavelength request terminates, the network decides for which class this wavelength is reserved. The best policy (the set of best actions for each possible state) is achieved by the Policy Iteration algorithm which maximizes the overall weighted utilization, using the discount cost model with infinite horizon. In [38], the same authors extend the work of [30] to grooming networks where traffic demands are usually subwavelength, with the goal to minimize the unfairness. Considering a single-hop single wavelength network, traffic is classified according to the bandwidth it requires. Thus, the network state is described by the number of existing calls of each class. Using this simple model, the optimal policy is examined. The authors also propose a heuristic to decompose tandem and ring networks using the idea of pre-allocating wavelengths for traffic with different $o - d$ pairs such that overlapping $o - d$ pairs do not share wavelengths (note that this is possible because the routing for all $o - d$ pairs are predetermined in the ring and tandem topologies). The numerical results show that substantial improvement in terms of fairness and utilization can be achieved compared to that of complete sharing policy and complete partitioning policy.

In [53], the authors study the fairness problem based on an auxiliary graph model, which consists of wavelength planes and different kinds of edges, which represent the availability of wavelengths, availability of grooming capability, the availability of transceivers and the source and destination of the traffic demand. In addition to grooming policies, two fairness policies are proposed. The fairness is evaluated in terms of the blocking probabilities of traffic demands with heterogeneous requests. The first policy sets a wavelength quota for each class of connections, distinguished by the rates they request. Since traffic demands requesting higher rates are more likely to be blocked, these classes receive more quota. Based on the quota, a dynamic grooming algorithm called wavelength quota method is proposed. The next policy is transceiver quota policy. Instead of counting the wavelength quota, transceiver quota is used to groom heterogeneous traffic demands in a manner as fair as possible.

Objective of Minimizing OEO — We noted earlier that OEO minimization is a common theme of static grooming. In this section we discuss literature that addresses the same objective in the dynamic context. In [23], Berry and Modiano address the dynamic traffic problems in SONET ring networks. The problem is defined as minimizing the number of ADMs while being able to satisfy a set of allowable traffic requests. The authors first lower bound the number of ADMs, which corresponds to the no grooming solution. A bipartite matching approach is then proposed to combine two solutions such that any one of the traffic requests can be satisfied while keeping the number of ADMs minimized. To study a specific and realistic dynamic traffic model, the t-allowable traffic model is introduced. The authors lower bound the number of ADMs and model it as a bipartite matching problem. Unnecessary ADMs are removed by applying a necessary and sufficient condition to support the t-allowable traffic. The authors extend the work to support dynamic traffic in a strictly non-blocking manner and show how hub nodes and tunability can further reduce the number of ADMs.

Hu studies the deterministic traffic model and present an ILP formulation with the goal to minimize the number of ADMs in [22]. Both unidirectional and bidirectional rings are studied. A nice observation for unidirectional rings proved in [22] is that the integer constraint for the variable x^r_{ijl}, the number of traffic circuits from node i to j in the rth traffic requirement that are multiplexed onto wavelength l, can be relaxed and turn the ILP into a MILP formulation that is easier to solve. Unfortunately, this is not true for the bidirectional case. Because of the routing problem involved (clockwise or counter-clockwise), the dynamic traffic grooming problem in bidirectional rings is much harder to solve. Some heuristic methods are proposed. Keeping the same set of constraints, the cost function is slightly modified by integrating the cost of wavelength and the cost of ADMs. The modified ILP formulation can provide an initial solution relatively easily. Then, a heuristic method is used to aggregate sub-wavelength circles into wavelengths.

To solve the same design problem, i.e., ring networks with a deterministic traffic model, in [42], two traffic splitting methods called traffic-cutting and traffic dividing are proposed to manipulate the traffic matrices. Starting from the all optical topology, the traffic-cutting method cuts the lightpath from source to destination at an intermediate node, combining the pieces with existing lightpaths as necessary to avoid requiring additional ADMs. The benefit is that, the traffic component can change its wavelength at the dropping node, which turns out to be more efficient in terms of the number of ADMs and wavelengths required. The traffic-dividing method allows traffic bifurcation, that is, different parts of a traffic component can be routed on different lightpaths. The authors propose a synthesized-splitting method that combines both the traffic-cutting method and the traffic-dividing method. A genetic algorithm is developed such that a given set of traffic matrices is satisfied in a strictly non-blocking manner.

In [24], the authors propose an ILP with the objective to minimize the number of transceivers for mesh networks, also under deterministic traffic, in the form of multiple traffic matrices. The ILP formulation explicitly rules out cycling of lightpath and routing. To solve the problem, a simple heuristic utilizing the time-varying state information is proposed. The sum of a traffic component's demands in every traffic matrix is used as a metric. Based on this metric, a traffic component is selected and either routed on the existing network or on a newly established lightpath (the choice is controlled by a predetermined parameter).

The study in [62] addresses the problem of deciding, based on the network state, when traffic grooming should be performed. The cost it considers is a function of the DXC ports and OXC ports. The network topology has two layers: the optical layer where optical express links (essentially, lightpaths) are connected by OXCs, and the physical layer where fiber links are connected by DXCs. Note that the OXCs and DXCs are physically decoupled. It is different from other studies where a grooming node is equipped with both an OXC and DXCs. A traffic request can be either routed on the physical topology (i.e., through DXCs) or on the logical topology (i.e., through OXCs). To decide between these alternatives, a parameter θ is defined as threshold, which should be tuned such that the overall cost is minimized. Both a centralized and a decentralized algorithms are proposed.

Kuri *et al.* study the mathematical model for Scheduled Lightpath Demands (SLDs) [16], which are in units of number of lightpaths. The cost is a function of the number of ports. By introducing the *Multi-Granularity Switching Optical Cross-Connects*, a waveband layer is inserted between the physical layer and the traffic demands. Hence in this context, grooming refers to aggregating and disaggregating lightpaths into waveband-switching connections of the virtual topology. Similar to the wavelength assignment problem in wavelength routed networks, SLDs are assigned routed scheduled band groups. Then, the SLD Routing (SR) problem and the SLD Routing and Grooming (SRG) problem are formulated as combinatorial optimization problems with the objective to minimize the cost. In [60], the authors extend the above work by taking subwavelength traffic demands into consideration. That is, a traffic demand can be decomposed into SLDs, that request a number of lightpaths, and a Scheduled Electrical Demand (SED), that requests part of a lightpath. The work is based on WDM networks with hybrid node architectures, i.e., a node consists of both an OXC and an EXC (same as a DXC). The problem is to find the size of the OXCs and EXCs that allow a network of a given topology to serve a given set of Scheduled Demands (SDs) at the lowest cost. To solve this problem for SEDs, the authors propose a simulated annealing based routing and grooming strategy.

The study in [61] is an extension of a previous paper by the same authors, where dominating set algorithms are proposed to solve the problem of the placement of wavelength converters. Because nodes with grooming capability are expensive, in this paper, the authors show that by appropriately selecting nodes, benefits of full grooming can be achieved with comparatively few nodes actually equipped with grooming capability. The traffic model studied is non-uniform. This is done by randomly assigning different nodes different weights and nodes with higher weight values generate more traffic than others with less weight values. Thus, the problem is modeled as the sparse grooming problem and formulated by the K-weighted minimum dominating set of the graph. A distributed voting algorithm is proposed and messages that are exchanged among nodes are introduced. Using these messages, a *Master* is selected and serves as the grooming node.

Other Approaches — In [35], the problem studied is a virtual topology design problem in mesh networks. The authors propose a formulation of the multi-hop dynamic traffic grooming problem, which aims at minimizing the network resource. The main difference of the formulation with those in other works is that the blocking probability is included as a constraint. The blocking model proposed is based on the concept of grooming links (g-links), where a g-link between two nodes is the set of possible lightpaths. A blocking model is proposed then to impose constraints on the number of lightpaths needed on g-links. The authors then present an ILP formulation that also imposes constraints on the maximum amount of by-pass traffic, the number of ports at each node, and the conversion capabilities.

In [55], the authors compare the performance and cost on different network architectures, the point-to-point network, single-hop network and multi-hop network. To take the network cost into account, the metric that is compared is in terms of the blocking probability versus the total arrival rate per dollar. To decide the cost for different network architectures, two steps are performed. First, the off-line network design step determines the hardware cost (the number of wavelengths, transmitters and receivers) for each architecture. After the off-line step, the on-line connection provisioning step that determines how the resources are used to accommodate dynamic traffic requests follows. In this step, a simple auxiliary graph based algorithm is used for each architecture. Simulation results show that multi-hop network is generally the best under a variety of cost scenarios. An interesting observation is that while the point-to-point architecture obviously has the lowest blocking probability, this is not the best choice if the cost of architecture is taken into account.

In [46], Elsayed addresses not only the dynamic routing and wavelength assignment problem but the fiber selection problem. The network studied has multiple fibers between each node pair. The original physical graph is folded out into *W* copies, where *W* is the number of wavelengths available on each fiber link. Since the nodes are wavelength-continuity constrained, these copies are isolated. Based on this layered graph, a modified Dijkstra's algorithm with reduced complexity is proposed to find a path for a source destination pair. Once the path is found, the fiber selection algorithm is called. Two selection methods, least-loaded fiber selection and best fitting fiber selection, are evaluated.

Srinivasan and Somani propose an extended Dijkstra's shortest path algorithm in WDM grooming networks [9]. Specifically, every node is assumed to be wavelength continuity constrained. The path vector is defined by the available capacity and hop-count. Two path vectors at a wavelength continuity constrained node are combined by taking the minimum capacity, which is different from the traditional Dijkstra's algorithm where costs are linear (i.e., additive). The authors then propose different policies to select paths based on the path vectors, namely Widest- Shortest Path Routing, Shortest-Widest Path Routing nd Available Shortest Path Routing. Finally, the algorithm is examined in terms of the request blocking probability, network utilization, average path length of an established connection, average shortest-path length of an accepted request and average capacity of an accepted request. In [56], the same authors make a comprehensive study on the comparative performance of different dynamic routing algorithms under different node architectures. The metrics in WDM grooming networks are classified as *concave* (e.g., the capacity of a path is the minimum capacity among the corresponding links), *additive* (e.g., the length of a path is the sum of the length of corresponding links), and *multiplicative* (e.g., the reliability of a path is the product of link reliabilities). Accordingly, depending on the node architecture, the link-state vectors are combined using different operations to form the path vectors. In addition to the approaches proposed in [9], a request-specific version of available shortest path routing is also studied. Finally, assuming traffic bifurcation is allowed, a dispersity routing algorithm is also evaluated. A counter-intuitive result noted is that increasing the grooming capability in network could degrade the performance under one of the algorithms.

The study in [18] addresses the algorithm design problem for multicast traffic in WDM grooming networks. The authors first introduce a node architecture that supports multicast traffic. To model the light-tree, a hypergraph logical topology is proposed, where a light-tree is represented as an arc (referred to as a hyperarc). For a multicast session, the destination nodes are represented by a supernode. Based on this hypergraph logical topology, the single-hop grooming approach and the multi-hop grooming approach are proposed. In the single-hop grooming, the hypergraph is searched for an available hyperarc for the new multicast request. In the multi-hop grooming, a hyperarc with the same supernode as the request and a single-hop lightpath from the source node of the request to the source node of the hyperarc are found. The multicast session is established on the combination of a single-hop lightpath and a light-tree.

CONCLUDING REMARKS

The dynamic traffic grooming problem is an important area to the research community as well as to service providers. In today's WDM networks, the increasing number of wavelengths available on an optical fiber and various optical/electronic equipment with different functionalities enable networks that are not only increasingly complex but also more and more agile. Accordingly, they provide more opportunity to balance the complexity (usually translated into cost) and the agility. In this sense, the dynamic traffic grooming problem is envisioned to be an essential area in the future.

In this article, we have presented a literature survey of the dynamic traffic grooming area. We started from the physical layer by discussing different optical equipment and their architectures. Then we classified the dynamic traffic grooming problem into the design and analysis problems, and discuss the formulation of the design problem as optimization or decision problems. Following the classification, we surveyed the literature thoroughly.

Although the dynamic traffic grooming problem has already been extensively studied, many practically important problems worthy of study still remain open. In the analysis class, models with limited complexity are needed. Models of high complexity are theoretically useful but may not see extensive practical application. In a similar sense, the models need to take the mesh topology, multi-rate traffic model and link load correlation into consideration. Current approaches often make restrictive assumptions such as very simple topologies, or link independence, that make them less practically useful to the network designer, even though they may provide good insight into the nature of the problem. In addition, since networks generally are upgraded instead of built from scratch, we expect that the network may very often have a heterogeneous architecture. Because of the distinctions between traffic grooming networks and traditional data/circuit networks, this problem is of particular interest.

In the class of design problems, we believe that under the umbrella of the dynamic traffic grooming problem, many more interesting and practical problems remain to be discovered and solved. For example, some particular traffic models may be of practical interest. As we mentioned above, the Scheduled Lightpath Demand (SLD) traffic model has been generalized in several directions, including that of subwavelength traffic. However, some interesting and practically important generalizations (such as sliding window scheduled demands) remain unaddressed in the subwavelength context. Another interesting problem is that of translating QoS requirements from different levels in the network. It is envisioned that GMPLS will be widely deployed as a management layer in next generation networks. Therefore, approaches to dynamically groom subwavelength LSPs onto lightpaths while taking the QoS requirements (e.g., delay) into consideration needs to be studied.

As the field evolves, traffic grooming may come to be seen as a general problem of network design where the cost component is largely concentrated into specialized network node equipment (as opposed to bandwidth, in yesteryear's networks). In the near future, minimizing OEO may well cease to be a worthwhile goal, if device technology makes appropriate advances. However, the presence of a large amount of dark fiber in the ground makes it likely that some other nodal equipment, such as optical drop-and-continue, wavelength converters, OTDM switches, or some other emerging technology will dominate network costs.

The issue of multicast and broadcast grooming has been addressed in the static context and there are some works in the dynamic context as well. However, it continues to be comparatively less explored. The increasing trend of using the Internet for content distribution for media applications requiring SLAs may well cause interest in this area to grow.

Another interesting development is likely to come from waveband grooming; wavebands or coarse wavelengths are optical channels created by less selective optical filters and transponder equipments, so that a number of usual lightpaths can be optically forwarded with the use of a single such waveband port. Thus the waveband introduced yet a third layer of topology in the design problem, and waveband grooming has already drawn the attention of researchers in the static context. Literature is soon likely to appear on dynamic waveband grooming.

Lastly, the lessons learned from traffic grooming may be applied to other areas of research in future. The emergence of wireless networks as viable metro area networks makes such wireless networks, and heterogeneous networks formed of optical and wireless domains, an interesting area of research. Such an environment is typically more dynamic than wireline networks. The desire to provide SLAs to wireless LAN customers introduces the theme of QoS to sub-circuit flows, which is a distinguishing characteristic of traffic grooming. In short, we expect many interesting and far-reaching research results to develop out of the comparatively new research area of dynamic traffic grooming. We hope that our survey, in a modest way, will help researchers newly entering this field.

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