Research Problems in Dynamic Traffic Grooming in Optical Networks [*]

Shu Huang and Rudra Dutta
Department of Computer Science,
North Carolina State University, Raleigh, NC 27695-7534
shuang5@unity.ncsu.edu, dutta@csc.ncsu.edu

Abstract

Traffic grooming has recently emerged as an important area in wide area wavelength-routed optical networks research. This research area addresses the problem of multiplexing lower rate traffic demands into wavelength channels of high bandwidth, so as to reduce network equipment cost by maximizing the optical (wavelength) routing and minimizing electronic routing. Recently, there have been efforts to extend studies of this kind to cases of dynamic traffic. However, this area is still comparatively new, and most of the proposed approaches ignore the optical routing maximization aspect in favor of simply considering blocking probability. In this position paper, we describe a range of problems that we consider appropriate for consideration under the umbrella of dynamic grooming, and show what the various dimensions are along which various flavors of this class of problems may be found. We provide some sample formulations describing some of these problems precisely.

1 Introduction

Wavelength-routed optical networks have long been recognized as the backbone networks of tomorrow. The attractive qualities of optical transmission, together with the technology of routing individual wavelength channels without the need for intermediate Opto-Electro-Optic (OEO) interconversion, has further made such technology attractive for a future in which the backbone will be characterized by the need for high speeds with highly predictable performance. The literature on the *virtual topology design* problem has focused on the possibility of forming *lightpaths* or clear optical channels that can then be viewed as traffic that must be routed and assigned wavelengths on the physical topology of the network.

Because optical networks are envisaged to be used in core networks, and also because when virtual topology problems were first considered it was not realized exactly how large the bandwidth of optical networks was going to be, it was deemed a reasonable assumption by most researchers that individual traffic demands would be comparable in bandwidth to whole lightpath(s). It has subsequently become clear that realistically they are typically considerably smaller, and such *sub-wavelength* traffic must be multiplexed (using electronic TDM methods) into individual wavelength channels to obtain good utilization of network bandwidth. This process has been called *traffic grooming*.

Network design with sub-wavelength traffic demands has grown more and more worthy of consideration because of several reasons. Optical networks are being extended closer and closer to end users, where more flexibilities to set up and tear down low speed traffic demands are required. GMPLS-aware *Optical Cross-Connect* (OXC) are expected to assign incoming LSPs to lightpaths (higher level LSPs) using some kind of traffic grooming algorithm. Again, because of the emerging optical technologies, the bandwidth available on a single wavelength is increasing, from 2.5 Gbit/s to 10 Gbit/s, probably even higher in future. In addition, although the number of wavelengths available on a single fiber by the use of *Wavelength Division Multiplexing* (WDM) is increasing, it is still one of the limitations in optical networks. *Optical Add-Drop Multiplexors* (OADM) can selectively switch some optical channels while dropping others to electronic equipment, but only by whole wavelengths. Thus assigning whole lightpaths to small sub-wavelength traffic demands will result in severe under-utilization of optical backbones.

1.1 Static Traffic Grooming Context

Most of the attention in literature has been so far focused on this problem when the node-to-node traffic demands do not vary significantly over time; *i.e.* when they are well-represented by a static matrix of traffic demands. The static grooming problem is a large optimization problem. Given the traffic matrix, a physical network and constraints such

---

[*] This research was supported in part by NSF grant # ANI-0322107

as the number of wavelengths per link, the objective of the design is to minimize the network OEO equipment cost in some sense. In terms of OEO, the costliest network design is one in which every node is *opaque*, that is all lightpaths traverse only one physical link and are terminated at every node (so no optical channel can pass through the node). The objective of design is to reduce the OEO requirements from this completely opaque case.

Several different cost functions have been studied. In [12], the authors studied SONET rings on multiple wavelengths, and argued that the first-order goal of the *wavelength assignment* (WLA) problem should be to minimize the number of SONET ADMs. This objective may be generalized to minimizing the *number of Line Terminating Equipment (LTE) needed* totaled over all the network nodes - a direct reflection of OEO equipment cost. The study in [12] showed that minimizing the number of ADMs is in general not equivalent to minimizing the number of wavelengths. In [4], heuristics to minimize the number of ADMs subject to the minimum number of wavelengths were also proposed.

Another candidate objective is *the overall electronic routing* performed, totaled over all the network nodes [9–11]. This model focuses on the cost of actual electronic processing involved in OEO routing. While it does not capture the cost of OEO equipment directly, it is a more fine-grained measure of the OEO routing, since it does not penalize the traffic actually originating or terminating at a node. It reflects the delay (and other possible drawbacks of OEO routing, such as possibility of error or buffer overflow loss during electronic processing) suffered by the traffic due to OEO routing more accurately, and may be more useful for QoS considerations at higher layers.

A third objective is to minimize *the maximum number of lightpaths originating/terminating at a network node*, as in [3]. This objective also directory focuses on LTE cost, but rather than attempting to minimize the total over the whole network, it concentrates on the node at which the largest such equipment must be deployed. The practical rationale for this is that all network nodes are often built identically in actual deployment, rather than with custom equipment at each node as would be required to implement a solution provided by total LTE minimization. This kind of min-max problems have been studied extensively in the context of traffic flow problems.

Many other network performance metrics are of practical interest, for example, the network throughput or minimum blocking rate [22]. The maximum network throughput problem and minimum network blocking rate problem are dual problems which have been studied extensively in the data network arenas. In the context of traffic grooming in optical networks, this model is at odds with the static traffic model where it is considered reasonable to assume that the fluctuation caused by individual traffic demands arriving or leaving are "smoothed out", and the aggregate traffic is effectively static. However, such assumptions are likely to become challenged in the future when traffic grooming considerations need to be extended into arenas where traffic exhibits more variation with time; indeed this is the subject of this paper. *However, it remains important to keep in mind that traffic grooming is a problem of OEO cost minimization*, as well as a problem of multiplexing. In the next section, we examine the traffic characteristics for which dynamic traffic grooming may be appropriate, and review current literature on the subject. Section 3 presents our views on the different flavors of problems that come under the area, and precise formulations for some specific problems. Section 4 concludes this paper.

In what follows, we refer to several *subproblems* commonly perceived as making up the traffic grooming problem. It is necessary to note that a practical solution to a traffic grooming problem will not necessarily consist of separate solutions to these subproblems; rather these are conceptually identifiable parts of the complete problem.

1. *Virtual topology design*, or deciding the set of lightpaths to establish. A virtual topology is a digraph $G(V, A)$, where vertices correspond to network nodes, with equipment such as OADMs, OXCs, etc., and there is an edge between two vertices *iff* there is a lightpath established between the corresponding nodes.

2. *Lightpath routing*, on physical links. This is a version of the general routing problem which has been studied extensively for decades. However, in this case, lightpaths represent the traffic demands. There may be specific additional constraints for lightpath routing in WDM networks; *e.g.* physical impairments such as loss, chromatic dispersion and nonlinear effects may constrain the physical hops in a lightpath. In general, the constrained routing problem is NP-Hard [1].

3. *Wavelength Assignment* to lightpaths, obeying the wavelength continuity constraint and avoiding wavelength clash. Wavelengths are one of the critical resources in optical networks. The number of wavelengths that can be multiplexed onto a single fiber is limited. The high costs of *Dense Wavelength Division Multiplexing* (DWDM) has given rise to *Coarse Wavelength Division Multiplexing* (CWDM). In [5], it was shows that the general WLA problem is NP-Complete by a reduction from the classical graph coloring problem.

4. *Traffic Routing.* Once the virtual topology has been decided and realized, the actual node-to-node traffic flows have to be routed over the lightpaths. This is again the general routing problem mentioned above.

2 Dynamic Traffic Grooming

Recently, the topic of dynamic traffic grooming has gained in interest. Reconfigurable optical add-drop multiplexors (ROADM) are becoming commercially available. This means that the concerns of all the above subproblems could be dynamically adjustable. In practice, this is seen as an opportunity to improve network performance by dynamically reacting to dynamically varying traffic.

Dynamic traffic must be considered because the traffic grooming locations are envisaged to be extending from core networks to metropolitan area networks and even further to end users. At such points, traffic demands are more likely to be much less than the capacity of a lightpath, and variations in them are less likely to be smoothed out by aggregation. We offer a highly idealized schematic view of the changing nature of traffic at various levels of aggregation corresponding to various levels of network from the end user to the core in Figure 1. It has two dimensions, the traffic peakedness/burstiness and the bandwidth requirement. In the legends, C indicates the bandwidth of a single wavelength, t represents the magnitude of the typical node-to-node traffic demand placed on the network, and Δt represents the magnitude of the typical variation seen in the traffic at individual traffic change epochs. We show only four levels of aggregation for the purpose of illustration. At the lowest level, individual traffic packets are generated, and the traffic bandwidth is very low while the burstiness is very high. In general, with successive levels of aggregation by stochastic multiplexing, we expect that the bandwidth of the traffic would increase, while the burstiness would be smoothed out. When the traffic is effectively static, as expected in the core network, the magnitude of the traffic may be comparable to full wavelength bandwidth, in which case a virtual topology design or some other approach to *Static Lightpath Establishment* (SLE) is appropriate. On the other hand, if the typical traffic magnitude is still sub-wavelength, static traffic grooming is the appropriate response. In the intermediate levels of aggregation, the variation in traffic is clearly sub-wavelength, but each variation is significantly smaller than the overall traffic magnitude. This would appear to be the appropriate domain for the as yet ill delineated field of dynamic traffic grooming. Note that from these stages, network policy might dictate burstization, thus artificially raising both traffic magnitude and burstiness. In that case, some *Dynamic Lightpath Establishment* (DLE) approach would be suitable, possibly *Optical Burst Switching* (of course, such techniques are also appropriate in other networks in which these characteristics arise not due to aggregation followed by burstization but some other mechanism).

2.1 Prior Work

Recently, studies on dynamic traffic grooming have appeared in the literature. Most of them consider discrete call arrival and departure models, and focus on the blocking probability experienced by sub-wavelength calls as the relevant performance metric.

In [7], the authors study the performance analysis problem on the traffic grooming in single hop mesh networks. A close-form formula is derived by introducing several simplifications such as a single-wavelength link (SWL) blocking model; converting the multi-rate arrivals into bulk arrivals and approximated departures; and assuming overflow traffic is Poisson. Then a reduced load model is used to compute the end-to-end blocking probability. Through simulations, the authors claim that the analytic model matches well with the numerical results. The work in [6] is an extension of [7] by taking multi-hop routing into consideration. The authors assumed a simple admission algorithm at a source node for each incoming traffic demands. Routing strategy is given such that the SWL model introduced in the previous work 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. The study in [16] also provides an analytical model for evaluating the traffic blocking performance. A Trunk-Switched-Network with full-permutation nodes model is assumed (each wavelength is a trunk). Multi-hop paths are decomposed into two-link paths and analyzed using multi-rate traffic model. Then taking the link load correlation into account, the two-link paths are extended to the general multi-hop case. The authors of [18] study the blocking probability on tandem networks, that is a unidirectional path virtual topology. The authors consider the multi-rate arrival model on existing lightpaths. A path network is first decomposed into subsystems comprising two adjacent nodes and analyzed exactly by a modification of Courtois' method. Using the multi-rate model, the conditional steady-state probability is computed. Then, the link load correlation is considered by proposing an iterative algorithm.

In [13], the authors study the dynamic traffic grooming problem with rearrangement on ring networks. The authors provide a reconfiguration algorithm, called bridge-and-roll (BR), such that the number of LTEs is reduced while keeping the network as bandwidth efficient as a full opaque network. Putting different constraints on the resource, some interesting traffic models are introduced to illustrate the algorithm. In addition, to reduce the cost of traffic disrupting, bounds are provided in terms of the number of BRs. The dynamic traffic grooming problem in Mesh networks using a graph model is studied in [21]. This model creates an auxiliary graph and by assigning different weights to the edges,

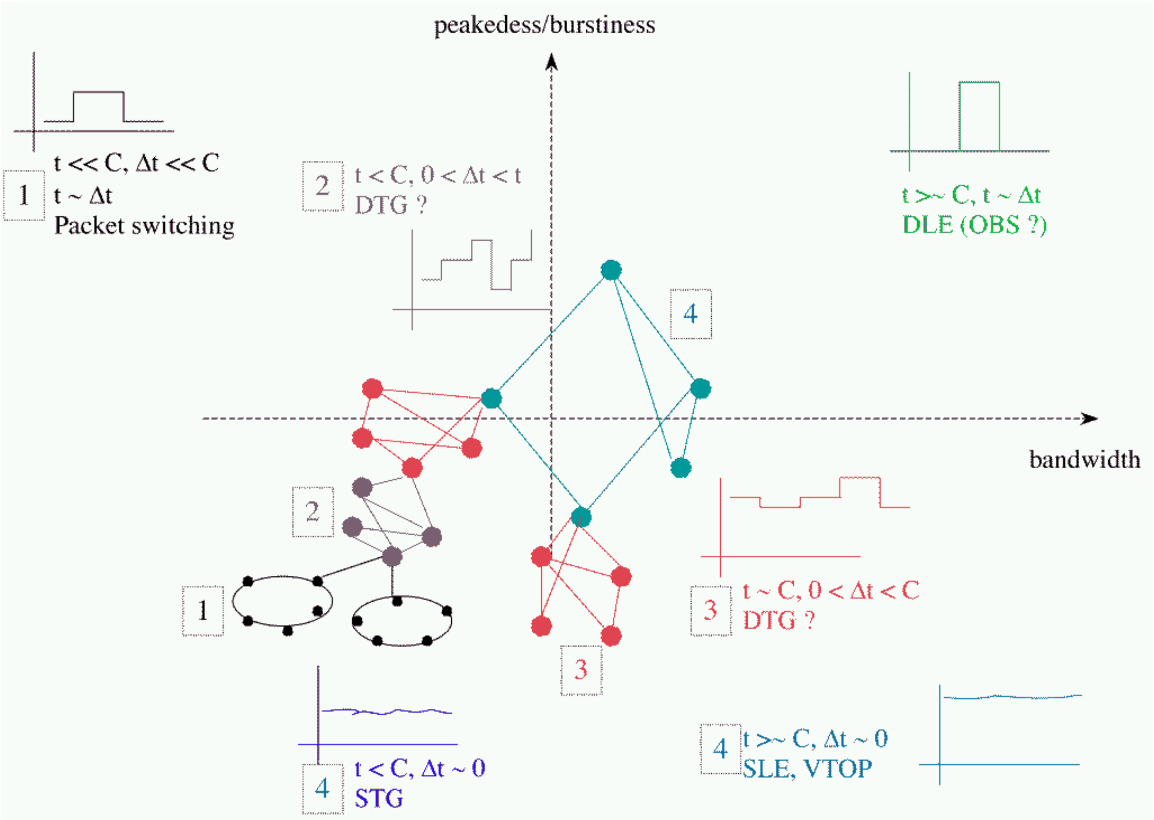

Figure 1. Schematic representation of different traffic characteristics

different grooming policies using various objectives can be implemented. The study in [19] also proposes some graph-based dynamic traffic grooming algorithms. The main constraints considered are the number of transceivers and wavelength continuity. The authors propose different graphs and links, upon which different routing algorithms for different grooming polices are introduced. The authors of [8] study the traffic grooming problem for WDM rings, both unidirectional and bidirectional, with the objective of minimizing the number of ADMs. A heuristic method in combination with the ILP formulation is proposed. The heuristic involves two phases, first, an ILP is solved to minimize the number of wavelengths; then, based on the solution provided by the first stage, "subwavelength circles" are combined into wavelengths such that the number of ADMs is reduced as much as possible. It is interesting to note that the first stage, solving an ILP can be computationally much easier than solving the same ILP with the objective to minimize the number of ADMs directly.

3 Research Problems in Dynamic Traffic Grooming

3.1 Different Flavors of Dynamic Grooming

While some of current work in dynamic traffic grooming has focused on analyzing the blocking characteristics of the network under given grooming strategies, others have continued to treat the OEO cost minimization design as the primary problem. Unfortunately, the given grooming conditions assumed by blocking probability studies are not necessarily very useful from an OEO design perspective; for example many such studies assume that the network is totally opaque, which means that the worst possible OEO situation is the one being analyzed.

We feel that these and other choices of assumptions give rise to a variety of problems that may all be called dynamic grooming problems. In table 3.1, we articulate dimensions along which these problems might vary. Most existing work on dynamic grooming can be categorized into these flavors; in addition, there are some that are not currently addressed in literature.

At the broadest level, we can classify possible problems into two categories, those of *analysis* and *design*. Current

Analysis (of Blocking Probability)	virtual topology assumption=?	given static	opaque [14, 18]
		dynamic, strategy given	single-hop [7]
			multi-hop [6]
	modelling technique=?	link load correlation	correlated [16, 18]
			uncorrelated [6, 7]
		traffic rate model	multi-rate [16–18]
			single-rate
	traffic variation model=?	arrival departure model	Poisson model
Design (Performance Optimization)	traffic variation model=?	arrival departure model	Poisson model
			incremental [15]
		traffic matrix constraints	peak constraint [2, 13]
		slightly varying	sequence of matrices
			set of matrices with probabilities
			increments, with probabilities
	objective of design=?	blocking probability	strict sense [2]
			wide sense
			rearrangeable [13, 20]
		utilization, delay	
		OEO costs	number of ADMs [2, 8]
			amount of electronic proc.
	virtual topology allowed=?	static	
		one per traffic pattern	
		sequence, schedule [13]	

Table 1. Different Flavors of Dynamic Grooming

studies attempting to analyze the behavior of networks with dynamic sub-wavelength traffic have concentrated exclusively on analyzing the blocking probability of a given network design, and the arrival-departure model of traffic variation. However, there is no reason why other metrics cannot be analyzed, possibly under other traffic models such as the slightly varying traffic we articulated in Figure 1.

Of the blocking probability studies, we distinguish two approaches in the blocking probability analysis. One assumes a given static virtual topology, the other assumes that the virtual topology is dynamic but strategies how to change the virtual topology are given (how to set up/tear down a lightpath, how to reconfigure the virtual topology, for example). In dynamic traffic grooming networks, one main concern is the modelling of the traffic demands. The performance problem has been extensively studied in other networks, such as data networks and telecom networks. However, the performance study in wavelength routed networks is even more complicated because of the integration of different subproblems. For example, because of the wavelength continuity constraint, correlated models may have to be used to get more exact blocking probabilities. Also, we need to consider bulk-arrival and bulk-departure systems (multi-rate), and overflow problems if setting up new lightpaths is allowed for traffic demands that are unable to be accommodated by the existing topology, which are unfortunately hard to study analytically. This broad class of studies has till date related more to prior queueing and blocking studies in other networking contexts, rather than to the traffic grooming area.

The other broad class, that of network design, has focused on developing the strategies for obtaining the virtual topology and traffic routing solutions, to optimize some objective (which may, indeed, be the blocking probability). As far as dynamic traffic grooming is concerned, the first question might be what traffic model is studied. Different models may form different problems. For example, we may have an arrival-and-departure model, or we can put different constraints on the traffic matrix, *e.g.*, degree constraints for each node, such that only some set of traffic matrices are allowed. We may also be interested in traffic demands that change slightly/slowly.

One main concern in networking problems is to optimize some kind of objectives which are subject to some constraints. Along this dimension, different flavors may be of interest. As we have mentioned, the blocking probability is an important metric that should be optimized. When the strict sense blocking probability is concerned, we may need to design a network (virtual topology, *e.g.*) such that the blocking probability for allowed traffic is minimized. Moreover, the blocking probability can be of interest in the wide sense, that is, minimized by further study on algorithms (RWA, grooming, etc.). Another approach is the reconfiguration problem. Reconfigurations take a static view of the network and optimize it globally; however, they may disrupt existing traffic, which is undesirable and can be formulated as a form of cost. Therefore, a trade-off between the reward and cost is to be achieved. Delay and utilization are also common metrics that are of interest. Generally, service providers always try to better the utilization before considering an upgrade of their networks and investment on new equipment.

As we have mentioned before, minimizing OEO cost is a primary concern for static traffic grooming, and it is reasonable to expect that the same concerns hold for dynamic traffic grooming. For example, when a network upgrade is necessary, we may need to find a solution such that the overall amount of electronic routing is minimized. A coarser objective that captures the network cost more directly might be to minimize the number of electronic ports. We remark that both objectives are directly important in the static traffic grooming problem; however, in dynamic traffic grooming, we are more interested in some *policy* that can be followed by the service provider so that the objectives can be optimized in some way.

Network management policy or other design circumstances may constrain the virtual topologies and traffic routing that can be used as a solution. For example, the solution can be constrained to make use of a single unchanging virtual topology; this can make the whole problem significantly simpler, but it loses the powerful flexibility of the virtual layer. Another possibility is to design a sequence of virtual topologies, one each for a set of traffic matrices. This approach seems to be amenable to analytic study due to the significantly reduced state space.

3.2 An ILP Formulation For the Static Traffic Grooming Problem

In order to create a baseline for formulating dynamic grooming problems, we first formulate the static grooming problem as a reference. ILPs for the static grooming problem exist in literature; however, we choose to formulate it afresh because the following formulation using node-arc matrices is particularly focused toward allowing generalization into dynamic problems.

We are given:

1. a physical topology $P = \{p_{i,mn}\}$, where $p_{i,mn}$ is f_{mn}, the number of fibers from node m to n, if $i = m$, $-f_{mn}$ if $i = n$ and 0 otherwise. We assume that $f_{mn} \in \{0, 1\}$,
2. the capacity of each wavelength C,
3. the number of wavelengths per physical link, W,
4. traffic demands, $T = \{t_{i,sd}\}$, where $t_{i,sd}$ is t^{sd}, the traffic demand from node s to d, if $i = s$, $-t^{sd}$ if $i = d$ and 0 otherwise. With loss of generality, we assume that $t^{sd} < C$,
5. the cost function.

We need to find:

1. a virtual topology, $V = \{v_{i,l}\}$, where $v_{i,l}$ is 1 if the lightpath l originates at node i, -1 if it terminates at node i, 0 otherwise,
2. the wavelength assignment, represented as a set of binary variables: $V^w = \{v^w_{i,l}\}$,where $v^w_{i,l}$ is 1 if the lightpath l originates at node i and uses wavelength w, -1 if it terminates at node i and uses wavelength w, 0 otherwise. Notice that, we have $V = \sum_w V^w$,
3. routing of the virtual topology, i.e., a route for each lightpath on the physical topology, represented as $B^w = \{b^w_{mn,l}\}$, $b^w_{mn,l} = 1$, if the lightpath l traverses the physical link $\{mn\}$ and uses the wavelength w, 0 otherwise,
4. the grooming scheme, let $F = \{f_{l,sd}\}$ be the traffic flow from node s to d, using the lightpath l.

The constraints imposed are:

- for the routing and wavelength assignment problem (RWA), we have:

$$PB^w = V^w \; \forall w \tag{1}$$

$$\sum_l b^w_{mn,l} \leq 1 \; \forall w, mn \tag{2}$$

- for the routing of traffic on the virtual topology, we have:

$$VF = T \tag{3}$$

- for the grooming problem, we have:

$$\sum_{sd} f_{l,sd} \leq C, \forall l \tag{4}$$

- nonnegativity and integer constraints:

$$b^w_{mn,l}, v_{i,l}, v^w_{i,l} \in \{0, 1\}, \; \forall l, mn, w \tag{5}$$

$$f_{l,sd} \in Z^0_+ \; \forall l, sd \tag{6}$$

Constraint (1) guarantees that a lightpath is assigned a wavelength and properly routed (assume no wavelength conversion); (2) guarantees that two lightpaths traversing the same link must be assigned with different wavelengths; (3) makes sure that traffic demands are properly routed on the virtual topology and (4) is the capacity constraint on each lightpath.

The objective can be represented as some linear function of all variables, without loss of generality, i.e.,

$$\min c^t(\{b^w_{mn,l}\}, \{v^w_{i,l}\}, \{f_{l,sd}\}).$$

We notice that the above constraints for the virtual topology routing and grooming subproblem, i.e., constraints (3) and (4), do not rule out the possibility of traffic bifurcation. In many practical cases it is desirable to forbid bifurcated routing, and in such a case an alternate formulation using path-flow indicators can be made. Note that new variables can also be used to form constraints forbidding any traffic component from describing a route on the physical topology that involves a loop. This would not be required in a traditional routing problem because such a solution would not be optimal; however, it may be appropriate here because a loop could form after a traffic component is routed on two successive lightpaths, each individually loop-free. Such a solution might not be automatically suboptimal if the cost metric relates to OEO cost. However, because of network management issues, such a solution might be undesirable. We do not discuss these extensions any further here.

Note that constraint (3) has product of two variables on its right-hand side, so it might appear that linearity has been lost in this formulation. Actually this is a notational convenience. $\sum_w V^w$ in this constraint can be replaced by a full mesh virtual topology with multiple arcs, represented as V_c, and the capacity constraint (4) would still continue to guarantee that traffic can only be routed on lightpaths that are actually available. Since V_c is a constant, the formulation has not lost its linearity.

Let the number of nodes be N, then the number of lightpaths is in $O(WN^2)$, the number of physical links in $O(N^2)$, the number of $S-D$ pairs in $O(N^2)$; thus we have $O(W^2N^3)$ nontrivial constraints. The number of variables is in $O(W^2N^4)$. We, of course, can combine arc flows into path flows, a representation that has much less number of constraints and larger number of variables. Using column generation technique, we will have a more efficient formulation.

3.3 An ILP Formulation For a Dynamic Traffic Grooming problem

From the ILP formulation, it is clear that the whole traffic grooming problem can be depicted as in Fig.2.

Now, suppose that the traffic demands change as a function of time τ. That is, we have $T_\tau = \{t_{i,sd,\tau}\}$. Let this information be provided over some period of time, from the initial time τ_i to the final time τ_f. The physical topology P of the network is assumed to remain constant over this period. From the sensitivity point of view, when T_τ changes to $T_{\tau'}$, the current solution remains feasible until the capacity constraints (4) become active. Thus, in order to satisfy the changing traffic matrices, the grooming solution is also a function of time. We denote the grooming solution as $SO_\tau = \{v^w_{i,l,\tau}, b^w_{mn,l,\tau}, f_{l,sd,\tau} \forall sd, l, mn\}$. As the traffic demands change, we possibly want to change the grooming, either because the existing grooming solution is infeasible, or the change is advantageous in the long run. However, changing the grooming does not come without cost. Without loss of generality, define the distance between two grooming solutions as $dist_{\tau\to\tau'} = ||SO_\tau - SO_{\tau'}||$, and assume that the cost function $\beta(\cdot)$ is a linear function of distance. This embodies the need to avoid frequent changes. Finally, the overall objective now becomes to minimize the overall OEO cost incurred over the entire period of time for which the traffic conditions are specified, *combined with* the cost incurred in all the changes of the grooming over that period.

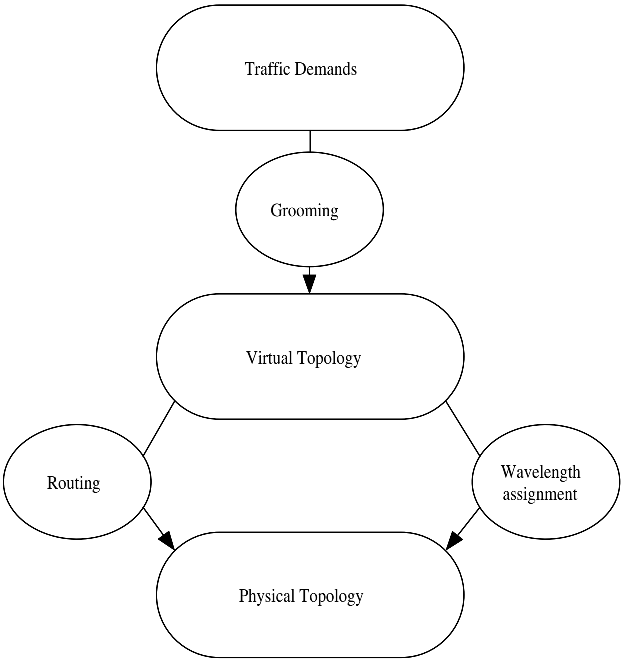

Figure 2. A layered view of the traffic grooming problem

To bring our previous concern into consideration, we have the following revised formulation:

$$PB^w_\tau = V^w_\tau \; \forall w, \tau \tag{7}$$

$$\sum_l b^w_{mn,l,\tau} \le 1 \; \forall w, mn, \tau \tag{8}$$

$$V_\tau F_\tau = T_\tau \; \forall w, \tau \tag{9}$$

$$\sum_{sd} f_{l,sd,\tau} \leq C, \ \forall l, \tau \tag{10}$$

Non-negativity and integer contraints must be imposed similarly as in the static case.

The objective we are interested in is:

$$\min\ \alpha\left(\int_{\tau_i}^{\tau_f} \sum_{sd}\sum_{l} f_{l,sd,\tau} d\tau\right)+\beta\left(\int_{\tau_i}^{\tau_f} d(dist_{\tau\rightarrow\tau'})\right),$$

where $\alpha(\cdot)$ is some cost function of the amount of electronic routing.

3.4 A Markov Decision Process (MDP) Formulation

In the case formulated above, all traffic changes are known to the network designer together with the times when changes occur. In this section, we consider the case when traffic variations are known only in statistical terms. Assuming that the processes of traffic arrivals are Poisson processes and the holding times are exponentially distributed, and decisions are made at the epoch when there is an arrival, the problem of determining the optimal policy constitutes a MDP problem. Note that, instead of using the transition rate from one state to another, we can easily convert the continuous-time MDP into an equivalent discrete-time MDP using the uniformization technique, such that the transition probabilities can be well defined. To consider the problem as an MDP problem, we need to define the MDP tuple $\{\mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}\}$, where $\mathcal{S}$ is the set of states, $\mathcal{A}$ is the set of allowed actions, $\mathcal{P}$ is the transition function, and $\mathcal{R}$, the reward function. It has been shown that the MDP formulation can be an effective tool in problems such as: Reconfiguration, Call Admission Control and Routing and Wavelength Assignment. Different problems may have different emphases. For example, in the call admission control (CAC) problem, actions are a call is accepted or not accepted; in the RWA problem, actions are a call is accepted or not and if accepted how to route it and assign it some wavelength; in the reconfiguration problem, actions are if reconfiguration should be undertaken and if so, how to reconfigure the network. The state space is the set of network states that will be affected by the corresponding actions. Different problems also have different objectives, generally, in terms of minimizing some cost functions. The cost function can be a combination of the cost paid to an action and the reward received when reaching a state. For a general description of the dynamic traffic grooming problem, in addition to theses subproblems, we need to consider the routing of sub-wavelength traffic. That is, the actions can be: whether a call is accepted or not (CAC); if accepted, how to route the call on the virtual topology (traffic grooming); if some new lightpaths are setup for the call, how to route and assign wavelengths for them (RWA); and if reconfiguration is performed, how to change the virtual topology and RWA (reconfiguration). The state space can be $\mathcal{S} = \{t_{i,sd}, v_{i,l}, b^{w}_{mn,l}, f_{l,sd}\forall i, sd, l, mn\}$. Unfortunately, the huge size of the state space of any realistic system defies an exact solution. However, focusing on different aspects and assumptions, a large number of variant MDP formulations exist. Next, we show a simple example that allows re-grooming of the existing traffic.

Assume that traffic arrivals are from different source-destination pairs and with different capacity requirements. In addition, arrivals are associated with different weights, which could be simply the capacity requirements or some other measures. When there is a traffic arrival, we have to make a decision whether to regroom existing traffic or not. The regrooming is done by choosing some traffic demands on the most congested lightpath and rerouting them on the least congested one or simply block them to make way for new arrivals. The selection list is sorted according to their weights, such that traffic with less weight is preferred. Therefore, the actions to be chosen is in $\{not\ regroom, reroute, block\}$. Let the state space at decision epoch l be $\mathcal{S}_l = \{N_l, T_l\}$, where N_l is the network state and T_l is the traffic matrix. Then, upon an arrival the next state at epoch l' is $\mathcal{S}_{l'} = \{N_{l'}, T_{l'}\}$, depending on the action taken ($\mathcal{S}_l$ can be equal to $\mathcal{S}_{l'}$). We classify the network states into two classes, $successful$, which means that all traffic demands are satisfied by the network, and $unsuccessful$, which means that some traffic demands are blocked. If the operation is $reroute$, we need to pay some cost for disrupting and delaying traffic, let it be $C(N_l, N_{l'})$; if some traffic demands are blocked, we lose some revenue, let it be $R(\mathcal{S}_l, \mathcal{S}_{l'})$. Then, what we are interested in is to minimize

$$\lim_{k\rightarrow\infty}\frac{1}{k}\mathbb{E}\left\{\sum_{l=0}^{k}\left[\alpha(R(\mathcal{S}_l, \mathcal{S}_{l'})) + \beta(C(N_l, N_{l'}))\right]\right\},$$

where $\alpha(\cdot)$ and $\beta(\cdot)$ are some nondecreasing functions of $R(\mathcal{S}_l, \mathcal{S}_{l'})$ and $C(N_l, N_{l'})$ respectively.

4 Conclusion

We have articulated the problem of dynamic traffic grooming in the context of the more traditional traffic grooming problem, and have discussed the traffic characteristics which are appropriate to consider for such problems. We believe this area is much broader than current literature suggests, and we have described the different dimensions along which different flavors of problems may be found. We feel that while blocking probability computations are important analytical tools, network design problems to minimize OEO cost continues to be a significant problem in the context of dynamic traffic grooming. Different methodologies can be used to formulate different problems in this area, and we have provided some sample formulations. We are currently working on designing good grooming algorithms for such problems, and hope to present results soon.

References

[1] R. Ahuja, T. Magnanti, and J. Orlin. *Network flows:theory,algorithms,and applications*. Prentice-Hall, 1993.

[2] R. Berry and E. Modiano. Reducing electronic multiplexing costs in sonet/wdm rings with dynamically changing traffic. *Journal on Selected Area of Communications,IEEE*, 18(10), 2001.

[3] B. Chen, G. Rouskas, and R. Dutta. Traffic grooming in WDM unidirectional paths and rings with min-max cost objective. In *Proceedings of Networking 2004, Athens, Greece*, pages 174–185, May 2004.

[4] A. Chiu and E. Modiano. Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks. *Journal of Lightwave Technology*, 18(1):2–12, Jan 2000.

[5] I. Chlamtac, A. Ganz, and G. Karmi. Lightpath communications: An approach to high-bandwidth optical wan's. *IEEE Transactions on Communications*, pages 1320–1340, 1992.

[6] C.Xin and C.Qiao. Performance analysis of multi-hop traffic grooming in mesh wdm optical networks. In *The 12th International Conference on Computer Communications and Networks*, 2003.

[7] C.Xin, C.Qiao, and S.Dixit. Analysis of single-hop traffic grooming in mesh wdm optical networks. In *Opticomm*, Oct 2003.

[8] C.Zhao and J.Q.Hu. Traffic grooming for wdm rings with dynamic traffic. manuscript, 2003.

[9] R. Dutta, S. Huang, and G. Rouskas. On optimal traffic grooming in elemental network topologies. In *Proceedings of OPTICOMM, Dallas, Texas*, pages 13–24, October 2003.

[10] R. Dutta and G. Rouskas. Traffic grooming in WDM networks: Past and future. *IEEE Network (to appear)*.

[11] R. Dutta and G. Rouskas. On optimal traffic grooming in wdm rings. *IEEE JOURNAL on Selected Areas In Communications*, 20(1):110–122, 2002.

[12] O. Gerstel, P. Lin, and G. Sasaki. Wavelength assignment in a WDM ring to minimize cost of embedded SONET rings. *Proceedings of IEEE INFOCOM*, pages 94–101, 1998.

[13] R. Kandula and G. Sasaki. Grooming of dynamic tributary traffic in wdm rings with rearrangements. Presented at the 39th Annual Allerton Confrerence on Communication, Control, and Computing, Monitcello IL, Oct 2001.

[14] K. Mosharaf, J. Talim, and I. Lambadaris. A markov decision process model for dynamic wavelength allocation in all-optical wdm networks. In *GLOBECOM2003*, volume 5, Dec 2003.

[15] G. Sasaki and T. Lin. A minimal cost wdm network for incremental traffic. In *Information Theory and Communications Workshop,Proceedings of the 1999 IEEE*, June 1999.

[16] R. Srinivasan and A. Somani. Analysis of multi-rate traffic in wdm grooming networks. In *Computer Communications and Networks, 2002. Proceedings. Eleventh International Conference on*, pages 296–301, Oct 2002.

[17] S. Thiagarajan and A.K.Somani. A capacity correlation model for wdm networks with constrained grooming capapbilities. In *Communications, IEEE International Conference on*, volume 5, June 2001.

[18] A. Washington and H. Perros. Call blocking probabilities in a traffic groomed tandem optical network,. *Special issue dedicated to the memory of Professor Olga Casals, Blondia and Stavrakakis (Eds.) Journal of Computer Networks*, 45, 2004.

[19] H. Wen, R. He, L. Li, and S. Wang. Dynamic traffic-grooming algorithms in wavelength-division-multiplexing mesh networks. *Journal of Optical networking*, 2(4), 2003.

[20] S. Zhang and B. Ramamurthy. Dynamic traffic grooming algorithms for reconfigurable sonet over wdm networks. In *Global Telecommunications Conference, GLOBECOM '02. IEEE*, volume 3, Nov 2002.

[21] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee. Dynamic traffic grooming in wdm mesh networks using a novel graph model. *Networking, IEEE/ACM Transactions on*, 11, 2003.

[22] K. Zhu and B. Mukherjee. Traffic grooming in an optical WDM mesh network. *IEEE Journal on Selected Areas in Communications*, 20(1):122 –133, Jan 2002.