On Traffic Grooming Choices for IP over WDM networks (Invited)

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Abstract

Traffic grooming continues to be a rich area of research in the context of WDM optical networks. We provide an overview of the optical and electronic grooming techniques available with focus on IP as the client layer. We discuss the various architectural alternatives available : peer, overlay and augmented models. We first provide a survey on the research work in the area of traffic grooming in optical circuit switched networks. We then identify problems with electronic grooming in terms of high speed router design and bring out the merits of optical grooming. Next, we describe the shared wavelength optical network technology called light-trails and compare its performance with electronic grooming networks for both the peer and overlay models. Based on our simulations on random graphs of various diameters, we identify the threshold router speeds at which light-trails can compete with the electronic grooming solution for a given network scenario. We conclude that since the present router capacities are below the threshold speed or such routers are likely to remain expensive for some time, light-trails is an appealing candidate solution.

1 Introduction

Grooming is a terminology that captures a variety of problems in telecommunication networks that aim to optimize capacity utilization. In an abstract generic sense, it is a complex multi-commodity network flow problem that involves different transport systems or multiple layers within the same system. The motivation for grooming arises because of the ability to share resources among multiple entities that need the resource. This sharing is possible and even desirable because the individual entities need only a fraction of the resource and multiplexing allows the resource cost to be amortized over the number of users. Three types of multiplexing are possible to increase transport bandwidth in optical networks [1] (a) space division multiplexing (b) wavelength division multiplexing and (c) time division multiplexing.

Grooming typically involves switching of traffic from one wavelength, waveband, time slot, fiber, cable to another [1]. Another feature that is fundamental to grooming is the ability to switch low speed traffic streams into high speed bandwidth trunks. Grooming devices include wavelength converters, fiber switch, optical crossconnects, electrical switches, time-slot interchangers and signal regenerators that can perform wavelength crossconnection. The general objective of grooming is to help decompose hard circuit provisioning problems into small, simpler ones and yield an increased solution space for such problems.

Given the generic nature of the problem, grooming has been studied along multiple dimensions. Traffic grooming can be provided within a layer or across layers. We call the grooming functionality that is built into the WDM layer, optical grooming and the grooming functionality that is available between the WDM and a client layer, electronic grooming. The WDM technologies that have built-in optical grooming are:

- Waveband switching (WBS)
- Shared Wavelength Optical Networks (SWON)
- Optical Burst Switching (OBS)
- Optical Flow Switching (OFS)
- Optical Packet Switching (OPS)

All these technologies share the key feature that they allow aggregation of smaller traffic units into larger pipes. The electronic grooming may be performed in the client layer and is typically either through SONET or IP. Since SONET is a TDM system, it has stringent timing restrictions and can act as a client layer only of the Optical Circuit Switched (OCS) WDM networks. IP, on the other hand, is packet/label switched network and hence can act as the client for any of above mentioned WDM technologies. IP grooming in WBS [2], OBS [3], and in SWON [4, 5] have gained increasing attention among the research community.

The focus of our current study is on two architectures - IP Over OCS-WDM and IP Over SWON swon.

The rest of the paper is organized as follows. In section 2, we describe some of the architectural alternatives available for IP over optical networks. Section 3 discusses details on some of the topologies, traffic models and cost functions that have been studied in the past. In section 4, we survey the progress in the field of IP traffic grooming for the peer, overlay and augmented models. We describe shared wavelength networks and identify some of its software and hardware requirements in section 5. We explain our problem statement in section 5 and explain our simulation results in section 6. We finally conclude the paper in section 7.

2 IP over optical networks

Networks have evolved over time to become a complex multi-layered protocol stack. It is not uncommon to find a system that runs IP over ATM over SONET over WDM. This hierarchy was required so that IP packets could be aggregated sequentially into label switched paths (LSPs), which can be further aggregated into SONET frames and finally transmitted over high bandwidth pipes. Each layer is popular for a certain functionality. For instance, IP was known for its interoperability while ATM offered signaling for QoS and traffic management. SONET provided fault tolerance, management and monitoring techniques while WDM was offered huge bandwidth. However, it can be seen that there are some functionalities like routing and survivability are implemented on all the layers. These overlaps could lead to even conflicting conditions unless the different layers are carefully coordinated.

With the development of MPLS control plane for IP networks, and the introduction of signaling through resource reservation (RSVP) and label distribution protocols (LDP), it is possible to allow explicit set up and traffic engineering of LSPs in an MPLS network [38]. This does way with the requirement of an intermediate ATM layer in the multi-layered stack. Over time, technology has matured to allow IP routers to run at wire speeds and yet meet various QoS requirements and achieve carrier class availability and reliability. This obviates the requirement of the intermediate expensive SONET equipment. The result is a slim IP over optical network as shown in figure 1 that consists of a multi gigabit label switched router (LSR) that directly connects to wavelength crossconnects (WXC) through ports with optical transmitters and receivers. This two layered stack is easier to manage and optimize for performance. From an architectural standpoint [37], an IP over optical network can be described using three different models: overlay, augmented and peer model. This classification is based on the amount of control information exchanged between the two layers.

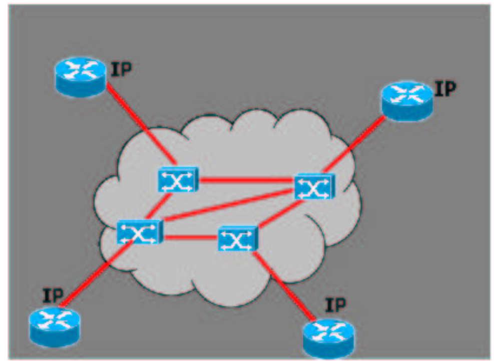

Figure 1. An IP over optical network

2.1 Architectural models

In the overlay model, the IP and optical networks are completely decoupled and a separate instance of a control plane runs on each network. The IP network (client) and has a well defined user interface with the optical network (server) called the UNI. The client can query the server over the UNI and get information about whether a particular connection between a router pair can be set up over the optical network. The IP/MPLS router maintains information regarding the residual capacities available on the existing logical topology and the available transceiver ports and router capacities. To serve a request, an IP router may decide to route it over the existing virtual topology or it may open new lightpaths. If it decides not to open up new lightpaths, it has to identify the virtual links over which the LSPs are to be routed. In the case, it wants to open up new lightpaths, it decides the LSR pairs between which the lightpaths are to be provisioned.

In the peer model, also known as the integrated model, the IP and optical network run a unified control plane. In this case, the Generalized MPLS can be used to provide the uniform control plane while LDP and RSVP along with their extensions can be used for setting up and tearing down LSPs and lightpaths. The LSRs have information regarding the optical network topology, the unused wavelengths and residual capacities on the logical links and transceiver ports in the network. This information is exploited to solve the LSP provisioning problem in the IP layer and the Routing and Wavelength Assignment problem in the optical layer in an integrated manner.

The peer model has a good potential to yield cost effective network solutions. But it is limited by the fact that LSRs and WXCs are typically managed by different vendors running proprietary protocols making the tight coupling scenario less practical. Also, it requires huge amounts of control messages to be flooded across entities to maintain global network status. The overlay model, does not exchange any information across layers and is easy to manage. But, it may lead to severe network under utilization. The middle ground that can be reached is the augmented model. The augmented model requires that some amount of useful information be exchanged between the optical and electronic layer. The control information is to be small enough to prevent large flooding and large enough to let the LSR make useful WDM aware routing decisions.

Research on traffic grooming mechanisms in IP over WDM network have focused primarily only on the peer model. While there is some limited research on the overlay model, there is only one reported work on the augmented model to the best of our knowledge. Note that some of the studies mentioned below are independent of the client layer and hence is not constrained to IP being the higher layer.

3 Traffic Grooming

It is known that in practical situations, the traffic arriving at an optical network is subwavelength in nature. Assigning a full wavelength to each request would result in poor network utilization. For effective bandwidth utilization, optical networks allow several independent traffic streams to share the bandwidth of a lightpath. The traffic grooming problem can be logically decomposed into four sub problems as described in [43].

1. Topology design subproblem: Determine the virtual topology to be embedded on the physical topology.
2. Connection routing subproblem: Route connections over the virtual topology.
3. Routing subproblem: Determine the route of each of the lightpaths over the physical topology.
4. Wavelength assignment subproblem: Allocate wavelengths to lightpaths subject to assignment and continuity constraints.

Traffic grooming in WDM has been studied extensively for various topologies: path, star, tree, ring and mesh networks. Grooming is inherently a hard problem. This can be seen from the fact that traffic grooming problem in path, star and tree topologies are NP-Complete [43]. Since the RWA for such topologies are trivial, this result brings out the hardness of the ’grooming’ aspect of the problem. For excellent surveys on traffic grooming, readers are referred to [15, 47, 40, 45]. The survey in [40] focuses on ring networks, while the survey in [47, 45] report research problems for in both ring and mesh networks. The work in [15] presents an ILP formulation and markov decision process formulation for the dynamic traffic grooming problem apart from giving an overview of research issues is dynamic grooming.

3.1 Cost functions

The objective of the grooming problem is to optimize a cost function that is typically one of the following

1. Minimize equipment requirements: add/drop equipment, OXCs, fibers, transponders, wavelengths, channels, time slots etc.
2. Minimize the total amount of electronic conversion and total amout of traffic routed
3. Minimize changes to existing topologies
4. Minimize Blocking probability
5. Minimize number of physical hops or logical hops
6. Maximize network utilization
7. Minimize the maximum number of lightpath terminations

3.2 Traffic models

Research work in the past has considered multiple type of traffic models: static, dynamic, incremental, matrix set, scheduled, and realistic traffic. In the static traffic model, all the requests are known in advance and do not change. The general objective in such studies is to minimize cost while accepting all requests or maximizing throughput with a given set of resources. Since, response time is not a constraint in static provisioning, time consuming ILP formulations, or meta heuristics like simulated annealing, genetic algorithms, and tabu heuristics have been proposed. In the dynamic model, calls are assumed to arrive at a certain rate and depart after some holding time with known distributions. The typical objective of such studies is to maximize network utilization or minimize blocking probability. Statistical models have been applied to analytically evaluate network performance in the presence of such traffic.

In the incremental traffic model, a call arrives dynamically but does not leave the system. The work in [52] conducted network planning across several years to produce a network that is can carry all the traffic at the end of the planning horizon. The authors of [49] use as input a set of different traffic matrices which is supposedly representative of time varying traffic and provides a configuration solution with an objective to minimize resource consumption.

The sliding scheduled traffic model was introduced in [22]. Here, the holding time of a connection is known in advance but the set up time is assumed to occur at any time in a prespeified time window. The work in [25] recognizes that poisson traffic models do not take into account the IP traffic elasticity and the interaction between the IP and optical layer. The authors propose two realistic traffic models and based on their simulations conclude that approximating IP traffic to be a CBR like traffic can lead to wrong conclusions when routing and grooming are considered.

4 Survey of grooming in OCS networks

We describe some of the research issues that have been studied for peer, overlay and augmented models. Our intent is not to be comprehensive but rather show some general trends in the approaches.

4.1 Peer Model

As mentioned earlier, majority of the work in the literature is geared towards the peer model. Broadly, they can be classified into two: analytical modeling and network design. We describe each in turn below.

4.1.1 Analytical approach

The work in [20] considers network nodes of two types: Wavelength Selective Crossconnect (WSXC) and Wavelength Grooming Crossconnect (WGXC) nodes. WSXC can switch traffic from one port to another but cannot switch streams between wavelengths. WGXC has the capability to switch signals in across fibers, time slots and across wavelengths. A network with only WSXC nodes are called constrained grooming networks while a network with some WGXC nodes are called sparse grooming networks. Analytical models with link independence assumption and capacity correlation assumption were designed to study the constrained grooming networks. The performance of networks with limited number of WGXC nodes were also modeled. The paper concludes that sparse grooming offers an order of magnitude decrease in blocking probability for high line-speed connections and multiple orders of magnitude decrease in blocking for low line-speed connections.

An analytical model to evaluate the blocking performance of grooming networks with heterogeneous grooming capabilities is discussed in [23]. The grooming network is modeled as a Trunk Switched Network which is a two-level network model in which every link in the network is viewed as multiple channels. Models with and without precise knowledge of the grooming architectures are considered and are observed to have similar performance.

Performance analysis of traffic grooming in mesh networks has been studied [24] in the presence of multi-granularity, multi-class, and multi-hop traffic. The single wavelength link is modeled using a queueing system based on continuous time Markov chains. Precise representation of the state will include the specification of traffic type in service, the number of client calls and the individual call bandwidths which may lead to state space explosion. Using the bulk arrival concept, the arrival of one client call is converted into the arrival of multiple fictitious micro calls, each having unit bandwidth and same service time. This reduces the state space to specify only the type of call and the number of micro-calls in service leading to a more tractable but approximate model. The link independence model is assumed and the blocking performance of both multi-hop and single-hop grooming were studied. The simulation results were found to be a good approximation to observations based on simulations. A similar model was studied in [48] to model sparse grooming networks.

4.1.2 Network Design and provisioning approach

We present some of the techniques that have been used in the literature for network design an provisioning for IP over optical networks. The review we present here can be classified as ILP based for static traffic, and auxiliary graph-, network flows- and clustering-based techniques for dynamic traffic.

ILP based techniques

The work in [21] studies the static grooming problem with an objective to maximize network throughput. An ILP based mathematical formulation is presented for single-hop and multi-hop grooming for multigranularity connection with non-bifurcation constraints. Two heuristics with one that maximizes single-hop traffic (MST) and the other that maximizes resource utilization (MRU) are presented. Simulations were performed to observe the throughput with limited number of transceivers and wavelengths and were compared with the optimal solution. The paper concludes that MRU performs better if tunable transceivers are used and MST performs better if fixed transceivers are used.

Auxiliary graph based techniques

A generic graph model for grooming static traffic in a heterogeneous grooming network environment is presented in [14]. The algorithm takes into account the heterogeneities in the network in terms of wavelengths, transceivers, conversion and grooming capabilities. Besides, it solves the grooming problem in a combined way in stead of splitting it into multiple sub problems and solving them independently. Three different policies were introduced, edge weight assignment principles were discussed and three traffic selection schemes were analyzed.

Online approaches for provisioning connections of different bandwidth granularities were dealt with in [53]. The grooming policy and route computation algorithms are discussed. For a connection to be established between two nodes, an attempt is first made to use an existing lightpath and if that fails to use a series of lightpaths. If the connection has not be accommodated yet, a new direct lightpath is set up or a mix of old and new lightpaths are used.

In [55], two route selection strategies are studied for the peer model. Both identify multiple alternate routes between a given source destination pair. One strategy always routes a new request along the most loaded route while the other strategy tries to balance the load along multiple routes. The work in [54] also proposes two strategies based on the layered graph approach - channel level balance (CLB) and link level balance (LLB) and show that LLB is better than CLB in most cases. The authors investigate the effects of wavelength conversion by studying multi fiber networks and conclude that when connection granularity is much smaller than wavelength granularity, wavelength conversion may lead to deterioration in blocking performance unless a connection admission strategy is used.

The problem of dynamic routing in the peer model with inaccurate link state information is studied in [56]. The consistency and completeness of routing information is vital to achieve improved network throughput. However, the wavelength and bandwidth information may not always be accurate. The objective of this paper is to minimize the set up failures and blocking probability that results due to partial information. A probabilistic mechanism is applied to model the uncertainty of link state parameters and a cost function that takes into account this uncertainty is used to compute the route. The authors conclude that with their algorithms the impact of inaccurate link state information is significantly reduced.

The authors in [27] propose a simple model for routing in peer model by assigning different weights to already existing circuits and new wavelength links. The special emphasis in the paper is on the signaling and protocol implementation aspects of the grooming scheme.

Network flow based techniques

The authors of [19] study the problem of traffic grooming to reduce the number of transceivers in optical networks. This problem is shown to be equivalent to a certain traffic maximization problem. An ILP formulation is presented and a greedy heuristic that uses the min cost flow problem is described. Simulation and ILP results were compared for uniform and random traffic pattern for small networks.

An algorithm for integrated routing for the peer model was presented in [36]. It uses a graph based approach that contains both the virtual and physical links. The model identifies all the min cuts for every possible ingress-egress pair and considers a link to be critical for this pair, if this link appears in at least on of its cuts. Each link is assigned a cost based the number of LSR pairs for which this link is considered critical. By discouraging a new flow from using these links, the amount of residual capacity in the network can be maximized at every iteration. However, the complexity of this heuristic is high sine it has to compute max flow for all node pairs.

Clustering techniques

The study in [28] uses a clustering technique called Blocking Island paradigm (BI) to propose an integrated grooming algorithm in peer model. BI provides an efficient way of abstracting resource availability in a communication network. BI clusters nodes in the network according to bandwidth availability. One of the distinct features of this paradigm is the ability to identify the existence of a route of sufficient capacity without having to compute a route based on shortest path algorithms. Since only a small segment or island of the network is studied, it is fast and scalable and yields better solutions than provided in [36].

A framework for hierarchical traffic grooming based on a clustering approach is presented in [42]. The authors of this paper decompose a network into multiple clusters and select a hub node which will act as the grooming hub for the traffic originating and terminating at local nodes. At the second level of the hierarchy, the hub nodes form a virtual cluster for the purpose of grooming intra-cluster traffic. While the work presented in [42] assumed that the clusters were already given, the work in [41] suggests a mechanism to choose clusters based on the K-center problem.

4.1.3 Network Survivability

The authors in [26] study the survivable design in IP over WDM peer networks by defining a concept called 'piecewise survivability'. This idea allows a given moderate or large topology to be contracted into a small topology which can then be studied to provably and efficiently verify the existence of survivable mapping in the original topology. They also propose an algorithm to search for a survivable mapping in a given topology and that can identify links to be added to an existing topology to make it survivable.

A protection scheme to dynamically allocate paths for the peer model is designed in [35]. While the physical link is assigned a unit cost, a logical link is given a cost that equals the number of physical links traversed by it. It introduces a control parameter that determines the relative preference of physical links and logical links during route selection. The analysis of the control parameter suggests that the treating a logical link as no different from a concatenation of physical links yields the best results.

Three approaches for shared protection have been proposed in [16] - protection at lightpath level (PAL), mixed protection at connection (MPAC) level and separate protection at connection (SPAC) level. Each strategy makes different levels of trade-off between wavelengths and grooming port. They conclude that it is beneficial to groom primary paths and backup paths separately, SPAC performs best when grooming ports are sufficient, and PAL performs best when grooming ports are small.

4.2 Overlay Model

The work in [39] focuses on designing a LSP-level shared and dedicated partial protection scheme for the overlay model. It allows for single hop primary paths but upto two hop shared backup path. It concludes that a combined IP and WDM layer protection scheme is more resource efficient than WDM level shared protection. It studies the blocking performance as a function of LSR speeds and concludes that high router capacities will be required to support systems with large number of wavelengths.

The authors of [29] propose a grooming heuristic for the overlay model that puts a constraint on the maximum number of hops allowed in routing a connection. Through analysis and simulations results, they show that there exists an optical hop constraint for each network configuration that leads to efficient capacity utilization.

The authors of [33] provide a MILP formulation for protection only in the IP/MPLS layer for the overlay model. By designing a simple heuristic, they conclude that a scheme that protects from both LSR failures and WDM single link failures costs only marginally more than a scheme that provides protection from LSR failures alone.

4.3 Augmented Model

The most significant contribution of the work in [34] is to identify a specific type of control information that could be exchanged along the IP and optical networks for the augmented model. The paper suggests that the WDM layer pass L_{ij}, the number of lightpaths that can be established between LSRs i and j, to the IP/MPLS layer. L_{ij} could be the number of common free wavelengths available on every link of the path identified by the routing algorithm. It is approximated that the amount of capacity available between i and j is the sum of residual capacities on the existing logical topology and the amount that could be used in the future (L_{ij}). By assigning a cost to the link that is inversely proportional to the total residual capacity, the algorithm achieves an order of magnitude improvement in results than provided in [36].

4.4 The problem with electronic grooming

Electronic grooming results in improved wavelength utilization, but, it also results in the lack of bit rate, encoding, and protocol transparency [46]. For instance, there needs to be an unified upper layer that performs the grooming functionality. With transparency being lost, seamless and cost effective up gradability feature of optical networks is also lost. Even with grooming being implemented in the network, best utilization is possible only through peer model which does not appear to be practical at the moment.

Another big source of concern is the feasibility of high speed electronics that does the grooming functionality. This is because routers have to process the transit traffic apart from handling the traffic sourced/sunk by the local node. The cost per electrical port is more expensive than cost per optical port. While an LSR can be faster than a table look up based router, the incoming LSPs will still have to be stored, scheduled and label swapped before switching out to the output port. The time available for processing and scheduling an LSP is drastically low at high router speeds.

With large router capacities, there is lots of output contention and hence fast arbitration is required. As mentioned in [57], for a 40 Gbps switch port with 40 byte packets, the arbitrator has only about 4 ns to resolve the contention. Buffer management and memory access speeds could prove to be a bottleneck in gigabit speed switches. A large router usually needs multiple racks with huge amounts of information being exchanged among the racks. The interconnect technology for the backplane is usually optical and is associated with high costs and excessive power consumption.

There is a growing gap between link and processor speeds [57]. With increasing line speeds, packets can arrive at a port at speeds exceeding the capability of a single processor. However, only packets of the same flow in the incoming stream have dependencies and hence the processing of independent flows can be distributed to several processors working in parallel. Therefore, an LSR is limited by the number of ports on and by the amout of aggregate switching capacity of the processors.

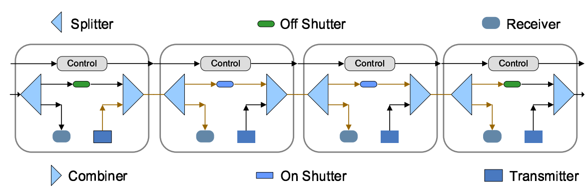

Figure 2. SWON node architecture

5 IP over SWON

The focus of this section is on optical grooming in SWONs - a concept that allows multiple connections to be groomed optically onto the same wavelength without involving electronic bottlenecks. Several variants of the optical grooming architecture has been introduced in the literature [6, 18, 51] and our work is based on [6] called the light-trail (LT) architecture.

The basic idea is as follows. Consider a circuit (LT) that is set up between nodes N_1 and N_4 that traverses the route $N_1 - N_2 - N_3 - N_4$ as shown in Figure 2. In networks with single hop grooming OXCs [12], only connections between N_1 and N_3 can share the same wavelength statistically. However, for the architecture described in [6], multiple downstream connections can be supported on the wavelength provided the aggregate sum of the requests do not exceed the capacity of the wavelength (capacity constraint). For instance, any subset of requests from { (N_1, N_2), (N_1, N_3), (N_1, N_4), (N_2, N_3), (N_2, N_4), (N_3, N_4) } can be carried on this circuit subject to the capacity constraint. More generally, a circuit that passes through N nodes can be designed to support up to $N(N-1)/2$ connections. This allows more choices for packing traffic into a wavelength and hence leads to better network utilization.

This wavelength sharing is made possible using a splitter, combiner and an optical shutter on every wavelength at every node. Consider the node N_2 mentioned above which has the necessary hardware for sharing. As packets from N_1 are sent over the circuit, the signals are split by the splitter. The data can be received by the node N_2 through a photodetector if N_2 is interested or it can be ignored by not provisioning a receiver for it. The line signal passes through the optical shutter which may be configured in the on/off position. If the node under consideration is an end node (N_1 and N_4) of the circuit, the shutter is configured in the off position to block the wavelength. For the other nodes (N_2 and N_4), it is configured in the on position to let it pass through.

For node N_2, the signals pass through the shutter to reach the combiner. The combiner is required so that the local node can transmit data into the same wavelength at a later time through a transmitter. Since multiple nodes are sharing the circuit, the medium is arbitrated using a MAC protocol. The shutters are configured statically during the provisioning time and is not switched on a per packet basis. A variant of architecture called source based light trails (SLT) allows only connections from the same source to be groomed by the wavelength. For instance, if the circuit above is set up as a SLT, only connections from a subset of $\{(N_1, N_2), (N_1, N_3), (N_1, N_4)\}$ can be carried subject to the capacity constraints. An important feature of SLT is that it trades off the requirement of MAC protocol for reduced grooming options. The SLT can be implemented through a simpler drop and continue architecture as described in [18].

The work in [6] designs a control plane protocol for set up and tear down of light-trail circuits. Simple MAC protocols have been proposed in [6, 9, 8, 10]. An ILP formulation for the trail routing problem was introduced and later heuristics were identified in [7]. A shared wavelength test bed was developed and demonstrated in [11].

A switch architecture for 'tune in' light-trails was proposed in [5]. This allows light-trails to first start out as lightpaths. The signals on the circuit is still available on the intermediate nodes but detectors are not provisioned to receive them. If the intermediate node is interested in a connection from the convenor node at a later time, it needs to simply tune the receiver into the trail. Readers are referred to [4], which presents the wavelength and transceiver requirements for the various architectures on a six node sample network in the presence of dynamic call arrivals. This work also discusses the tradeoffs made by LP, LT and SLT architectures in terms of performance, design complexity, hardware and software requirements.

SLTs allow same source data to be shared along a simple path. Light-trees [17] allow same source data to be shared along a tree like topology. This idea was first introduced in [12] and later extended in [17]. We do not consider such architectures further since they require power splitters that may result in tight optical power budgets.

6 Problem Discussion

The premise of our current approach is as follows. Due to the limitations mentioned above in designing high speed routers, it is clear that cost effective commercial technologies required for achieving hundreds of Gbps may not be available yet. An LSR may be designed by provisioning more ports than its core capacity can handle. For instance, consider an LSR that has 10 Gbps ports and a core switching capacity of 35 Gbps. It may appear that this LSR can be equipped only with 3 router ports. However, grooming may not be able to pack all the transceivers to 100 % since packing is an inherently hard problem and may not yield good packing fraction per transceiver port. So, the LSR may choose to support 4 ports and let the grooming algorithm ensure that the aggregate traffic rate at the router does not exceed 35 Gbps.

The extra port on the router may be useful in improving the blocking performance of the network. The important thing to note here is that the transceiver itself may not be all that expensive as compared with the switching fabric. Based on this, it is seen that LSRs are not only limited by the number of ports but also by the aggregate switching capacity. Our objective is to study how grooming performance is affected by limited switch core capacities. Specifically, we compare the performance of LP, SLT, LT and TG networks for the overlay and peer models. For LP, LT and SLT, there is no electronic grooming involved and hence the routing algorithm is not different for the overlay and peer models.

LP heuristic:

We maintain W layers of the physical network. We also maintain a separate virtual topology layer which consists of links between any node pair which has a lightpath set up between them. When a request arrives, the LSR tries to route on a virtual link (if it exists) between the source destination pair in the virtual topology. If it fails, the WDM layer tries to route on any of the W layers of the graph with an objective to minimize physical hops traversed. We call this heuristic LP.

SLT and LT heuristics:

In both LT and SLT networks, each node maintain a database of trails on which they are involved. The node may or may not be active on the trail on the transmission (reception) side. If it is active, it has a transmitter (receiver) already provisioned on this trail. Otherwise, the equipment is not provisioned but the circuit can be 'tuned into' at any time. When a connection arrives, a trail that passes through both the source and the destination is identified. If there are multiple such trails, the one where the node is active is preferred. If this does not exist, a trail of shortest physical length is chosen. If no trail from source to destination exists, a new set of wavelength links are opened up.

TG heuristics:

For TG, we use the auxiliary graph based approach proposed in [53]. A chosen request can be routed from a source to a destination on a network in one of the following ways: on a direct lightpath (C1), as a concatenation of multiple lightpaths (C2), as a concatenation of multiple free wavelength links (C3), as a concatenation of both light paths and free wavelength links (C4).

For the overlay model (TG-OY), the objective is to route on the logical topology first before opening up new wavelengths. So, we try to route according to C1, C2 and C3 in that order and use the first case that does not fail. If all the attempts fail, the request is rejected.

For the integrated model (TG-IV), the objective is to minimize the number of virtual hops. We try C1 failing which we try C2. If both fail, we chose from C3 and C4, the route that leads to minimum virtual hops. If all steps fail, the request is blocked. We experimented with minimizing the number of physical hops and found that for the specified scenario it did not yield results that are significantly different from TG-IV and so we do not report them here.

Network	α	β	Links	Diameter	W	T
N1	0.4	.2	158	5	10	17
N2	0.4	.1	121	8	15	25
N3	0.25	.09	99	10	25	25
N4	0.1	.09	85	16	30	30

Figure 3. Parameters for the random graphs that were used for the simulations

7 Simulation Results

We compare the performance of overlay and peer mechanisms for the four different architectures described in the earlier section. For the purpose of running these heuristics, we use the Waxman graph model for generation of random topologies. In this model, n nodes are randomly distributed over a rectangular grid indexed by integer coordinates. The edges are introduced between nodes s and d with a probability given by,

$$P(s,d) = \beta e^{-\frac{D(s,d)}{L\alpha}}$$

where D(s,d) is the euclidean distance from node s to node d, L is the maximum distance between two nodes, and α and β are parameters in the range (0,1]. Large values of β results in graphs with higher edge densities and small values of α increases the density of short edges relative to long ones. We generate four different topologies (N1 through N4) of various diameters for our simulations and the parameters associated with these graphs are given in figure 3. We estimate the capacity blocking performance of the schemes on all the four topologies. We experiment with different topologies to see if the results hold for different networks equipped with different resources. We ensure that all the graphs generated are at least two connected.

7.1 Simulation Parameters

All the networks studied in our work are assumed to have 40 nodes. Each wavelength has 10 Gbps capacity. The request arrivals are poisson distributed and stay in the network for an exponentially distributed time period whose rate is normalized to unity. The individual requests are uniformly distributed among the various node pairs. The requests have distinct granularities 1 to 5 Gbps and their probability distribution is such that, if combined capacity of calls to a node pair is Kg, where g is the number of distinct granularities, each request size contributes a capacity of K. For each point generated in the graph, we simulate 100,000 requests on a 3 GHz Pentium IV processor and 512 MB RAM to obtain the network performance results which takes upto a maximum of 5 minutes to run.

In all the results provided here, a traffic load of 300 Erlangs was carried in the network except if stated otherwise. Figure 4(a) plots the capacity blocking probability as a function of IP router speed for the integrated model run on the small diameter topology (N1). The number of transceivers and wavelengths provisioned for the network are provided in Figure 3.

7.2 Results and Discussion

In Figure 4(a), LP has the worst blocking performance, as expected. There is minimum one order of magnitude difference in performance of LT as compared with LP. SLT is positioned somewhere between LP and LT. The number of

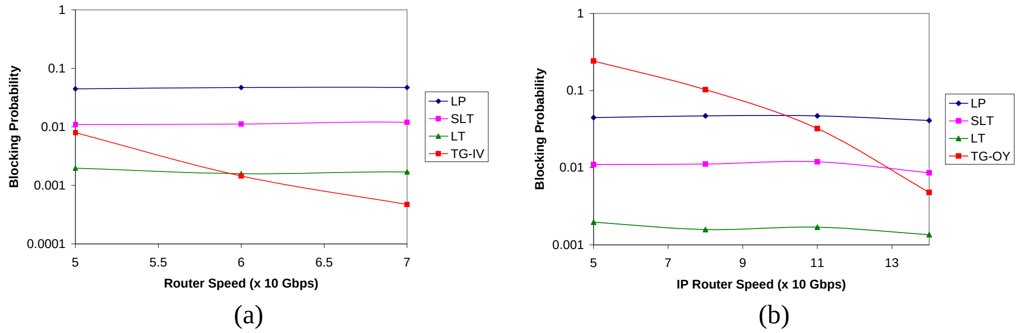

Figure 4. Blocking performance as a function of IP router speed (a) for the integrated model on the small diameter network N1 (b) for the overlay model on the small diameter network N1

grooming choices for SLT is less as compared with LT since SLT can only optically groom requests that originate from the same source. The choices for LP are even lower since it can only groom requests between the same source destination pair. The minimum router speed is set to be above the maximum capacity originated or sunk by any single node. Hence the performance of LP, LT and SLT do not change with change in router speed.

For TG-IV, The blocking performance improves with increase in router speed. For router speeds less than 60 Gbps, LT performs better than TG-IV. This is because TG-IV requires the routers to electronically process a lot of transit traffic while grooming. Even if wavelengths and transceivers in the network have sufficient residual capacities to groom requests, the router speeds are not sufficient to process some of the requests and hence they are dropped leading to lower performance than LT. At a certain threshold speed, the router capacities exceed the load offered by both the source/sink traffic and transit traffic and hence the blocking performance improves and is better than LT.

We ran our heuristics on many random graphs of varying nodal connectivities and observed similar behavior. We do not present the results here for lack of space. We observed that the router speed at which TG-IV outperforms LT increases as the network diameter increases. This is because more grooming needs to be performed due to the frequent unavailability of long wavelength continuous routes in large diameter networks. This results in more transit traffic being processed by the intermediate routers and consequently requiring higher speeds. The point here is that the router speed at which TG performs better than LT can be found from this graph. If the current technology supports such router speeds, it may be a good idea to provide electronic grooming. Otherwise, LTs are good candidate solutions to be considered until the higher speed routers are available.

Figure 4(b) studies the performance of different architectures assuming overlay model on the network N3. Since the route identification mechanisms are the same as earlier for LP, SLT and LT, there is no difference in their relative performances. TG-OY performs worse than even LP for certain router speeds. This is because TG tries to route the requests first on the logical topology. This leads to a saturation of router capacities earlier on in the simulations due to transit traffic handling. When a new request arrives, even if wavelengths and transceivers in the network have sufficient residual capacity to carry it without grooming, sometimes, the routers at the source or the destination may not have the processing power to handle it. Hence, the request may have to be dropped leading to abysmal blocking performance. For both the medium and large diameter networks, it is observed that, LT does better than TG-OY. This is not true for all loads. At this point, we are working to identify possible wavelength, transceiver and router capacity combinations along with the traffic-topology mix for which LT can be a competing solution as compared with TG.

Figure 5 plots blocking probability as a function of load for network N2. We study the effect of load at two router speeds : 30 Gbps and 50 Gbps. We use the term TG-IV-30 to indicate the results for grooming in the context of peer model at 30 Gbps router capacities. We show only the peer model for the sake of clarity and since the peer model performs much better than the overlay model. The graph shows that performance of all heuristics deteriorate with increase in load. For a given router speed, TG-IV does better than TG-OY as expected (not shown in the graph) since the integrated model has a better visibility into the optical network. For loads greater than 110 E, LT does better than TG-IV-30. This is because at high speeds, the amount of transit and local traffic at a node in the grooming network far exceeds 30 Gbps and hence leads to blocking making it fall behind LT. However, it is seen that TG-IV-50 outperforms LT for all specified loads.

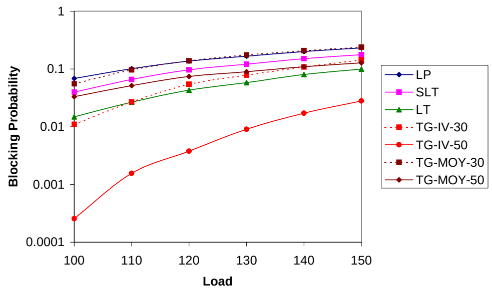

Figure 5. Blocking performance as a function of load for two router speeds - 30 Gbps and 50 Gbps

8 Conclusions

We reviewed some of the recent research work in IP over OCS and IP over SWON networks. We also outlined some of the traffic models that have been studied, the different cost models that have been used and the various techniques that have been applied to study traffic grooming in OCS networks. Next, we described the concept of optical grooming and observed that light-trails provide an order of magnitude better blocking performance as compared with non groomed lightpaths for random graphs of varying diameters. We observed that sometimes, it is possible that groomed lightpaths cannot do better than light-trails because they are constrained by the router capacities. In such cases, light-trails can be a good interim candidate solution. We are currently studying networks of various connectivities to identify scenarios where light-trails can compete with grooming lightpath networks.

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