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IV

TRAFFIC GROOMING

Chapter 11

TRAFFIC GROOMING IN WDM NETWORKS

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Abstract In today's WDM networks, the dominant cost component is the cost of electronics, which is largely determined by how traffic is groomed at each node. Therefore, the issue of traffic grooming is extremely important in the design of a WDM network. In this article, our goal is to introduce various aspects of the traffic grooming problem to the reader. We start with the static traffic grooming problem and illustrate how it can be solved based on the Integer Linear Programming formulation and various heuristic approaches. We then discuss variants of the problem including grooming dynamic traffic, grooming with cross-connects, grooming in mesh and IP networks, and grooming with tunable transceivers.

Keywords: Wavelength Division Multiplexing (WDM), traffic grooming.

11.1 Introduction

Wavelength Division Multiplexing (WDM) is emerging as a dominant technology for use in backbone networks. WDM significantly increases the capacity of a fiber by allowing simultaneous transmission of multiple wavelengths (channels), each operating at rates up to 40Gbps. Systems with over 80 wavelengths are presently being deployed and capacities that approach several Terabits per second can be achieved. While such enormous capacity is very exciting, it also places a tremendous burden on the electronic switches and routers at each node that must somehow process all of this information. Fortunately, it is not necessary to electronically process all of the traffic at each node. For example, much of the traffic passing through a node is neither sourced at that node nor destined to that node. To reduce the amount of traffic that must be electronically processed at intermediate nodes, WDM systems employ Add/Drop multiplexers (ADMs), that allow each wavelength to either be dropped and electronically processed at the node or to optically bypass the node electronics, as shown in Figure 11.1.

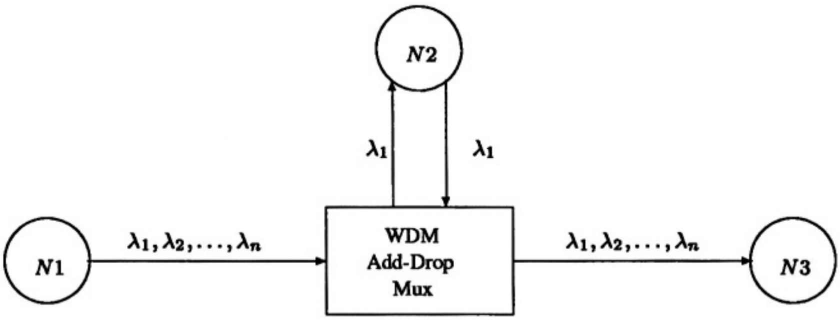

Figure 11.1. Using ADM to provide optical bypass.

Much of today's physical layer network infrastructure is built around Synchronous Optical Network (SONET) rings. Typically, a SONET ring is constructed using fiber (one or two fiber pairs are typically used in order to provide protection) to connect SONET ADMs. Each SONET ADM has the ability to aggregate lower rate SONET signals into a single high rate SONET stream. For example, four OC-3 circuits can be multiplexed together into an OC-12 circuit and 16 OC-3's can be multiplexed into an OC-48. The recent emergence of WDM technology has provided the ability to support multiple SONET rings on a single fiber pair. Consider, for example, the SONET ring network shown in Figure 11.2a, where each wavelength is used to form an OC-48 SONET ring. With WDM technology providing dozens of wavelengths on a fiber, dozens of OC-48 rings can be supported per fiber pair using wavelength multiplexers to separate the multiple SONET rings. This tremendous increase in network capacity, of course, comes at the expense of additional electronic multiplexing equipment. With the emergence of WDM technology, the dominant cost component in networks is no longer the cost of optics but rather the cost of electronics.

The SONET/WDM architecture shown in Figure 11.2a is potentially wasteful of ADMs because every wavelength (ring) requires an ADM at every node. As mentioned previously, not all traffic needs to be electronically processed at each node. Consequently, it is not necessary to have an ADM for every wavelength at every node, but rather only for those wavelengths that are used at that node. Therefore, in order to limit the number of ADMs required, the traffic should be groomed in such a way that all of the traffic to and from a given node is carried on the minimum number of wavelengths. As a simple and illustrative example, consider a unidirectional ring network (e.g., Uni-directional Path

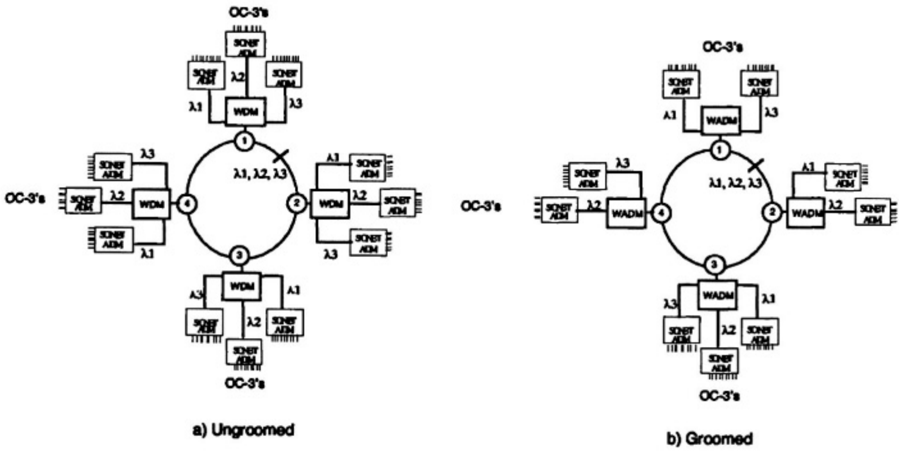

Figure 11.2. SONET/WDM rings.

Switched Ring, UPSR) with four nodes. Suppose that each wavelength is used to support an OC-48 ring, and that the traffic requirement is for 8 OC-3 circuits between each pair of nodes. In this example we have 6 node pairs and the total traffic load is equal to 48 OC-3's or equivalently 3 OC-48 rings. The question is how to assign the traffic to these 3 OC-48 rings in a way that minimizes the total number of ADMs required. Consider, for example, the two traffic assignments listed in Tables 11.1 and 11.2. With the first assignment, each node has some traffic on every wavelength. For example wavelength λ_1 carries the traffic between nodes 1 and 2 and the traffic between nodes 3 and 4. Therefore, each node would require an ADM on every wavelength for a total of 12 ADMs. With the second assignment each wavelength contains traffic from only 3 nodes and hence only 9 ADMs are needed. Notice that both assignments carry the same amount of total traffic (8 OC-3's between each pair of nodes). The corresponding ADM allocations for both assignments are shown in Tables 11.1 and 11.2, respectively.

In a bi-directional ring the amount of electronics is determined not only by how circuits are groomed but also by how circuits are routed (since a circuit in a bi-directional ring can be routed either clockwise or counter-clockwise) and how wavelengths are assigned to grooming lightpaths, i.e., the traffic grooming problem has to be considered in combination with routing and wavelength assignment (RWA) problem. Together, we have a traffic grooming and routing and wavelength assignment (GRWA) problem. A special case of the GRWA is the routing and wavelength assignment problem when all circuits are light-

Table 11.1. Assignment #1.

	Circuits
λ_1	between nodes 1 and 2 between nodes 3 and 4
λ_2	between nodes 1 and 3 between nodes 2 and 4
λ_3	between nodes 1 and 4 between nodes 2 and 3

Table 11.2. Assignment #2.

	Circuits
λ_1	between nodes 1 and 2 between nodes 1 and 3
λ_2	between nodes 2 and 3 between nodes 2 and 4
λ_3	between nodes 1 and 4 between nodes 3 and 4

paths (i.e., no grooming is needed). RWA is important to allow end-to-end lightpaths to share common ADMs [11]. In a SONET Bi-directional Line-Switched Ring (BLSR), an ADM is responsible for adding/dropping both the upstream and down stream data. This is done so that the data in one direction can be switched to the opposite direction in case of a failure. Consequently, if an ADM has working traffic in one direction of a lightpath (for example, upstream), and is not supporting traffic in the opposite direction (down stream), then its capability is not fully utilized and the bandwidth in the unused direction is wasted. This is analogous to what is commonly called stranded bandwidth in BLSR except it is occurring at the lightpath level.

To illustrate the importance of RWA of (groomed) lightpaths, compare the two RWAs, listed in Tables 11.3 and 11.4, of the same set of nine lightpaths, $\{1 \Leftrightarrow 2, 1 \Leftrightarrow 3, 2 \Leftrightarrow 3, 4 \Leftrightarrow 5, 4 \Leftrightarrow 6, 5 \Leftrightarrow 6, 7 \Leftrightarrow 8, 7 \Leftrightarrow 9, 8 \Leftrightarrow 9\}$, for a BLSR with 9 nodes ($i \Leftrightarrow j$ indicates a bi-directional lightpath between node i and node j). In these assignments, the circuit from i to j is routed in the direction opposite to the circuit from j to i. In RWA #1, all circuits are routed via shortest paths, while in RWA #2, circuits are more cleverly packed to make efficient use of the ADMs in both directions. For example, on λ_1 circuits $1 \Leftrightarrow 2$ and $2 \Leftrightarrow 3$ are routed via the shortest path, while $1 \Leftrightarrow 3$ is routed along the "longer path" $3 \Leftrightarrow 1$. Both RWAs support the same set of traffic demands. The first RWA uses 15 ADMs and 2 wavelengths, and the second RWA uses more wavelengths, but it only requires 9 ADMs.

The above example also illustrates a few characteristics of the overall problem of network cost minimization. First, the minimum number of ADMs is often not achieved with the minimum capacity usage. In the example, the method that uses the minimum number of ADMs requires an additional wavelength. Standard RWA algorithms that focus on minimizing the number of wavelengths cannot be directly applied to ADM cost minimization. Instead algorithms that attempt to jointly optimize the cost of ADMs and Wavelengths

Table 11.3. **RWA #1.**

	Lightpaths	ADMs
λ_1	$1 \Leftrightarrow 2, 2 \Leftrightarrow 3, 4 \Leftrightarrow 5$ $5 \Leftrightarrow 6, 7 \Leftrightarrow 8, 8 \Leftrightarrow 9$	9
λ_2	$1 \Leftrightarrow 3, 4 \Leftrightarrow 6, 7 \Leftrightarrow 9$	6

Table 11.4. **RWA #2.**

	Lightpaths	ADMs
λ_1	$1 \Leftrightarrow 2, 2 \Leftrightarrow 3, 3 \Leftrightarrow 1$	3
λ_2	$4 \Leftrightarrow 5, 5 \Leftrightarrow 6, 6 \Leftrightarrow 4$	3
λ_3	$7 \Leftrightarrow 8, 8 \Leftrightarrow 9, 9 \Leftrightarrow 7$	3

are more desirable (e.g., see [17, 31] for the joint optimization problem). Second, the minimum number of ADMs is not achieved with shortest path routing. Since shortest path is desired to reduce network latency, a tradeoff exists between network latency and ADM costs. Lastly, the RWA example shows that ADM saving is possible by appropriate RWA without the aid of grooming. This gives us two methods in reducing ADMs: grooming and RWA of groomed lightpaths. It would be tempting for a network planner to design the network in two steps: 1) low level grooming of tributaries onto lightpaths and 2) RWA of the resulting lightpaths. Unfortunately, this two-step process will lead to a sub-optimal solution. In fact, it was shown in [11] that an improvement of up to 20% could be achieved if the two steps are jointly considered in the design process.

Both grooming and RWA have the characteristic of grouping and packing problems. Such problems are often difficult. This intuitively explains why the ADM minimization problem is so complex. In fact, it was shown in [23] that traffic grooming problem is NP-complete by showing that the Bin Packing problem can be transformed into the traffic grooming problem in polynomial time. Since the Bin Packing problem is known to be NP-complete the traffic grooming problem must be NP-complete as well. As a result, many papers on grooming rely on heuristics and simulations to evaluate the heuristics.

As we mentioned earlier, the majority of optical networks in operation today have been built based on the ring architecture, however, carriers have increasingly considered the mesh architecture as an alternative for building their next generation networks, which have a compelling cost advantage over ring networks and are also more resilient to various network failures and more flexible in accommodating changes in traffic demands. On the other hand, in order to capitalize on these advantages, it is even more important to efficiently groom traffic in mesh networks. Similar to bi-directional rings, the traffic grooming problem for mesh networks has to be considered in combination with RWA. But RWA is much more complicated for mesh networks since circuits can be routed more flexibly in mesh networks.

In this article, we attempt to expose the reader to the basics of the traffic grooming problem. Our discussion is in no way meant to be an exhaustive exposition of the vast literature on the topic. Good survey articles on traffic grooming literature can be found in [9], [24]. In the next section we introduce the static grooming problem and discuss both the Integer Linear Programming formulation and heuristic approaches to its solution. In subsequent sections we discuss variants of the problem including grooming dynamic traffic, grooming with cross-connects, grooming in Mesh and IP networks, and grooming with tunable transceivers.

11.2 Grooming Static Traffic

The static traffic grooming problem is a special instance of the virtual topology design problem. Given a traffic demand of low rate circuits between pairs of nodes, the problem is to assign traffic to wavelengths in such a way that minimizes the number of ADMs used in the network. Virtual topology design problems can be formulated as a mixed integer programming problem. In the next subsections we discuss the integer linear programming (ILP) formulation for the traffic grooming problem followed by heuristic algorithms for solving the grooming problem.

11.2.1 ILP Formulation

We start by introducing the integer linear programming (ILP) formulation for the traffic grooming problem. The ILP formulation has been previously used in [8, 29, 17] for the traffic grooming problem. In [8], the objective function considered is electronic routing and the goal there is to derive bounds based on the ILP formulation. In [29], the authors concluded that the ILP formulation is not computationally feasible for rings with 8 nodes or more. Hence, they propose instead to use methods based on simulated annealing and heuristics. In [17], a more efficient mixed ILP (MILP) formulation is proposed for unidirectional rings which results in significant reduction in computation time. The numerical results provided in [17] show that optimal or near-optimal solutions can usually be obtained in a few seconds or minutes for unidirectional rings with up to 16 nodes. The work of [17] is extended to bi-directional rings and dynamic traffic in [31]. The ILP formulation is also used in [18] to study the traffic grooming problem for mesh networks.

In order to illustrate the ILP approach, we will focus exclusively on uni-directional rings here; however, the interested reader can refer to the above references for more general formulations. Consider a uni-directional WDM ring with N nodes. We assume that all available wavelengths have the same capacity and there may be multiple traffic circuits between a pair of end-nodes, but all traffic circuits have the same rate. The traffic granularity of the network is defined as the total number of low-rate traffic circuits that can be multiplexed onto a single wavelength. For example, if each circuit is OC-12 and the wavelength capacity is OC-48, then the traffic granularity is 4.

In designing a WDM ring, the key is to determine which ADMs are needed at each node. This mainly depends on how lower-rate traffic circuits are multiplexed onto high-rate wavelengths. An ADM for an individual wavelength is needed at a node only when the wavelength needs to be dropped at the node, i.e., when that wavelength is carrying one or more circuits that either originates or terminates at that node. If the wavelength only passes through the node, then no ADM for the wavelength is needed. Our objective is to find an optimal way to multiplex lower-rate traffic circuits so as to minimize the total number of ADMs required in the network. However, we can easily incorporate other considerations into our objective as well, such as the total number of wavelengths used in the network.

To present the ILP formulation, we need to introduce the following notation:

N: the number of nodes in the ring;

L: the number of wavelengths available;

g: the traffic granularity;

m_{ij}: the number of circuits from node i to node j $(i, j = 1, 2, \ldots, N)$;

$$x_{ijsl} := \begin{cases} 1 & \text{if the } s\text{-th circuit between nodes } i \text{ and } j \text{ is multiplexed} \\ & \text{onto wavelength } l; \\ 0 & \text{otherwise;} \end{cases}$$

$$y_{il} := \max_{s,j}(x_{ijsl}, x_{jisl})$$

$$= \begin{cases} 1 & \text{if any circuit with node } i \text{ being one of its end-nodes is} \\ & \text{multiplexed onto wavelength } l, \\ 0 & \text{otherwise;} \end{cases}$$

We note that if $y_{il} = 1$, then wavelength l needs to be dropped at node i, which implies that an ADM for wavelength l is required at node i. Since our objective is to minimize $\sum_{i=1}^{N} \sum_{l=1}^{L} y_{il}$, the total number of ADMs required in the ring, the traffic grooming problem can be formulated as the following integer linear programming (ILP) problem:

$$\begin{aligned}
\text{min} \quad & \sum_{i=1}^{N}\sum_{l=1}^{L} y_{il} & & \\
\text{s.t.} \quad & \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{s=1}^{m_{ij}} x_{ijsl} \leq g & l = 1,2,\ldots,L \quad & (11.1) \\
& \sum_{l=1}^{L} x_{ijsl} = 1 & \forall\, i,j,s \quad & (11.2) \\
& y_{il} \geq x_{ijsl} & & \\
& y_{il} \geq x_{jisl} & \forall\, i,j,s,l \quad & (11.3) \\
& x_{ijsl}, y_{il} \text{ are all binary variables} & &
\end{aligned}$$

The three constraints in the above ILP are:

(11.1): The total number of circuits multiplexed onto wavelength l should not exceed g.

(11.2): Each circuit has to be assigned to one (and only one) wavelength.

(11.3): Given that the objective is to minimize $\sum_{i=1}^{N}\sum_{l=1}^{L} y_{il}$, it is equivalent to $y_{il} = \max_{s,j}(x_{ijsl}, x_{jisl})$.

In general, it is computationally infeasible to use the above ILP formulation to solve the traffic grooming problem for large rings. In [17], it is shown how the ILP formulation can be improved so that it can be solved more efficiently. For example, the binary integer constraint on x_{ijsl} can be relaxed, resulting a mixed ILP which can be solve rather easily. The ILP formulation can be easily applied to bi-directional rings ([17]) and mesh networks ([18]). Other extensions of the ILP formulation include: a) non-uniform traffic ([17]), b) minimizing the number of wavelengths, or a weighted summation of the number of ADMs and the number of wavelengths ([17, 31]), and c) dynamic traffic ([31]). In [31], it was shown how the ILP formulation can be used in combination with heuristics to solve the traffic grooming problem.

11.2.2 Heuristic Algorithms

While the general topology design problem is known to be intractable, the traffic grooming problem is a special instance of the virtual topology design problem for which, in certain circumstances, a solution can be found. For example, [23] considers traffic grooming for a unidirectional ring and [27] considers the same problem for a bi-directional ring. Both [23] and [27] show that significant savings in the number of ADMs can be achieved through efficient traffic grooming algorithms. For example, shown in Figure 11.3 is the number of ADMs required when using the traffic grooming algorithm developed in [23] for the unidirectional ring with uniform traffic (single OC-3 between each pair of nodes groomed onto an OC-48 ring). This number is compared to the number of ADMs required when no grooming is used (i.e., all wavelengths are dropped at all nodes). It is also compared to a lower bound on the number of ADMs. As can be seen from the figure, the algorithms developed in [23] are not far from the lower bound, and achieve significant ADM savings.

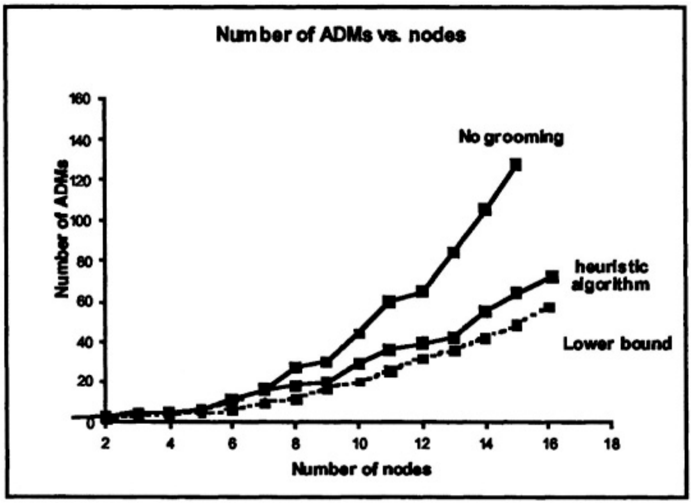

Figure 11.3. ADM savings in a unidirectional ring network.

The algorithms in [23, 27] consider three different traffic scenarios: 1) uniform traffic in a unidirectional and bi-directional ring, 2) distance dependent traffic where the amount of traffic between node pairs is inversely proportional to the distance separating them, and 3) hub traffic where all of the traffic is going to one node on the ring. All of those cases yielded elegant algorithms that are nearly optimal. The algorithms in [23, 27] are based on efficient "grouping" of circuits, where all circuits belonging to a group are assigned to the same wavelength and that wavelength is dropped at all of the nodes that belong to that group. Groups are chosen in such a way that the ratio of the number of circuits in a group to the number of nodes is maximized. This approach aims at making efficient use of ADMs. In fact, the algorithms are shown in [23] to be nearly optimal for uniform traffic and these "grouping" algorithms can also serve as the basis for solving the traffic grooming problem for general traffic. Of course, the general traffic grooming problem with arbitrary traffic is much more challenging. As stated earlier, the general problem can be formulated as an integer program. However, these integer programs are typically very computationally complex and can only be solved for very small problems that are often impractical.

Zhang and Qiao [30] make an attempt at solving the problem by separating the problem into two parts. In the first part, the heuristic packs the traffic demands (e.g., OC-3's) into "circles" where each circle has capacity equal to the tributary rate (OC-3) and contains non-overlapping demands. As many circles as needed are constructed to include all traffic demands. The second part of the heuristic groups circles into wavelengths (e.g., sixteen OC-3 circles in one OC-48 ring). Note that this algorithm is different than the two-step process mentioned in the previous section. There, the two steps are 1) grouping of tributaries into lightpaths, and 2) RWA of lightpath segments. Here, the two parts are 1) fitting tributaries onto a circle, and then 2) grouping of the circles. For this algorithm, the number of ADMs needed for a particular wavelength equals the number of "end nodes" involved, An end node is a node that terminates a connection in the circle. To minimize the number of ADMs, the heuristic attempts to match as many end nodes as possible when grouping the circles. This two part algorithm can achieve good performance for uniform traffic as long as the grooming factor is reasonably large (e.g., OC-3's onto OC48 wavelengths). Even for non-uniform traffic, this two part algorithm performs reasonably well if a good end-node matching algorithm is utilized. A similar two-step approach is also used in [31] for the traffic grooming problem with dynamic traffic, where the first step is solved based on the ILP formulation (instead of heuristic algorithms).

More recently, a number of researchers have developed heuristic algorithms for the traffic grooming problem with provable "worst case" performance bounds. These algorithms are known as approximation algorithms. For example, [10] and [5] consider the traffic grooming problem in a bidirectional ring with loopback protection and develop polynomial-time algorithms with a worst case performance of 8/5 (i.e., the algorithms developed are within 8/5 of the optimal).

11.3 Grooming Dynamic Traffic

Most earlier work on the grooming problem considered static traffic. Static traffic is common for many applications where a service provider designs and provisions network resources based on some estimate of the traffic. In many cases, however, the traffic changes over time, Such changes can be due to slow changes in traffic demands over a long period of time. More recently such changes can be attributed to the more rapid dynamics of Internet traffic. It is therefore important to design networks that are able to efficiently accommodate changes in traffic. There are three different models that have been used to characterize dynamic traffic:

Stochastic Model In this model, traffic requests (between a pair of nodes) arrive according to a stochastic point process and each request may last a random amount of time.

Deterministic Model In this model, traffic is represented by a set of different traffic requirements that the network needs to satisfy, but at different times. Each traffic requirement contains a set of demands. For example, the different traffic requirements can be a result of traffic fluctuation in different operation periods (morning, afternoon, and evening). Note that the static traffic case becomes a special case of this model in which there is only one traffic requirement for the network (and it never changes).

Constrained Model In this model, traffic demands between nodes are not specified. Rather, only a set of constraints on the traffic requirement are provided, such that the total amount of traffic at each node does not exceed a certain limit and/or the total capacity requirement on each fiber link does not exceed a certain limit

To the best of our knowledge, the traffic grooming problem with dynamic stochastic traffic has not been studied in literature, though the stochastic traffic model has been used in the study of other design problems for optical networks, such as the problem of wavelength conversion and blocking (e.g., see [1, 2, 28] and references therein). The constrained traffic model is used in [3, 15, 14, 26], where the focus is on obtaining lower and upper bounds on network costs (such as the number of ADMs required). The model in [3] defines a class of traffic called ***t*-allowable** which allows each node to source up to t circuits. These t circuits can be destined to any of the nodes in the network without restriction, and the destinations of the circuits can be dynamically changed. The approach taken is to design a network so that it can accommodate any ***t*-allowable** traffic matrix in a non-blocking way. The problem is formulated as a bipartite graph matching problem and algorithms are developed to minimize the number of wavelengths that must be processed at each node. These algorithms provide methods for achieving significant reductions in ADMs under a variety of traffic requirements. The deterministic traffic model is first considered in [3], In [17], the traffic grooming problem with dynamic deterministic traffic is formulated as an integer linear programming problem for unidirectional rings. In [31], an approach based on a combination of ILP and heuristics is proposed to study the traffic grooming problem with dynamic deterministic traffic. First, the ILP formulation was used to solve a slightly different traffic grooming problem in which the objective is to minimize the total number of wavelengths. This problem is much easier to solve than the traffic grooming problem whose objective function is the total number of ADMs. Once a traffic grooming solution with minimum number of wavelengths is obtained, it can then be used to construct a solution with as few ADMs as possible based on a heuristic method. As we mentioned earlier, this two-step approach of minimizing the number of ADMs was first used in [30] for the traffic grooming problem with static traffic. However, only heuristic algorithms were used in [30] to minimize the total number of wavelengths.

11.4 Grooming with Cross-Connects

Another approach for supporting dynamic traffic is to use a cross-connect at one or more of the nodes in the network. The cross-connect is able to switch traffic from one wavelength onto any other to which it is connected. Not only can the addition of a cross-connect allow for some traffic dynamics, but it can also be used to reduce the number of ADMs required. In [23] it was shown that using a hub node with a cross-connect is optimal in terms of minimizing the number of ADMs required and in [12] it was shown the cost savings can be as much as 37.5%. The proof in [23] is obtained by showing that any traffic grooming that does not use a cross-connect can be transformed into one that uses a cross-connect without any additional ADMs. In [13] various network architectures with different amount of cross-connect capabilities are compared.

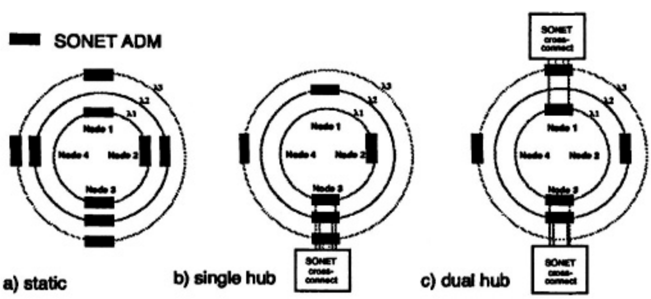

Figure 11.4. Grooming with cross-connect.

To illustrate the benefits of a cross-connect architecture, consider three possible ring architectures for the purpose of efficient grooming: a static ring without cross-connects, a single-hub ring, and a ring with multiple-hubs. With the static architecture no cross-connecting is employed, hence each circuit must be assigned to a single wavelength that must be processed (dropped) at both the source and the destination. The single hub architecture uses a large cross-connect at one hub node. The cross-connect is able to switch any low rate circuit from any incoming wavelength to any outgoing wavelength. With this architecture, each node sends all of its traffic to the hub node where the traffic is switched, groomed and sent back to the destination nodes. In the multiple hub architecture, K hub nodes are used on the ring. Each hub node has a small cross-connect that can switch traffic among the wavelengths dropped at that node. Each node on the ring sends a fraction of its traffic to one of the hub nodes, where it is properly groomed and relayed to its destination. These three architectures are depicted in Figure 11.4. Shown in Figure 11.4a is the static grooming solution where one wavelength is used to support traffic between nodes 1, 2 and 3, another for traffic between 2, 3 and 4, and a third wavelength for traffic between 1, 3 and 4. The hub architecture shown in Figure 11.4b has each node send all of its traffic to the hub located at node 3, where the traffic is groomed and relayed back to its destination. Finally shown in Figure 11.4c is the multiple hub architecture where each node can send its traffic to one or more of the hubs.

To illustrate the potential benefit of the multiple hub architecture, consider a unidirectional ring with 9 nodes where each wavelength supports an OC-48 and traffic demand is uniform with two OC-12's between each pair. In this case each node generates 16 OC-12's or four wavelengths of traffic. With the single hub solution, each node can send all four wavelengths worth of traffic to be groomed at the hub at say node 1. In this case, each node would use 4 ADMs, and the hub would use $8 \times 4 = 32$ ADMs for a total of 64 ADMs. In a 2-hub architecture each node would send two wavelengths worth of traffic to each hub (at nodes 1 and 5) and an additional wavelength would be used for traffic between the two hubs, resulting in 58 ADMs. Finally a 4-hub architecture can be used where each node sends one wavelength to each of four hubs and some additional ADMs are used to handle the inter-hub traffic. Using the grooming algorithm given in [21] and [22], a 4-hub architecture can be found that requires only 26 wavelengths and 49 ADMs. Notice that in this case the number of hubs is equal to the number of wavelengths generated by a node. Also notice that in increasing the number of hubs from 1 to 4 the required number of wavelengths in the ring is reduced from 32 to 26. Thus the 4-hub architecture is more efficient in the use of wavelengths as well as ADMs.

It was shown in [20] and [22] that significant savings could be obtained by distributing the cross-connect function among multiple nodes. In [22] a lower bound on the number of ADMs is given as a function of the number of switching nodes (i.e., nodes with cross-connect capability), and algorithms that very nearly meet the lower bounds are provided. In fact, for uniform traffic, [21] shows that the number of electronic ports is reduced when the number of switching nodes (hubs) used is approximately equal to the number of wavelengths of traffic generated by each node. These savings are significant in two ways. First, the use of multiple cross-connects can reduce the number of ADMs needed. Second, using multiple smaller cross-connects rather than one large cross-connect at the hub reduces the cost of the cross-connects. The above papers all conclude that the use of cross-connects for grooming adds flexibility to the network over a static solution that does not use a cross-connect. This flexibility allows traffic to be provisioned dynamically thereby reducing the need to know the exact traffic requirements in advance. Another benefit of this flexibility is that the network will be more robust to node failures.

11.5 Grooming in a General Mesh Network

Most of the early work on grooming has focused on the ring topology. This is largely due to the fact that many networks employ SONET technology that is most often used in a ring topology. However, due to the growth in Internet traffic, an increasing number of networks are being arranged in a general mesh topology. This is because in many cases mesh networks have a compelling cost advantage over ring networks. Also, mesh networks are more resilient to various network failures and more flexible in accommodating changes in traffic demands (e.g., see [7, 16] and references therein). Therefore, there is a need to extend the grooming work to general mesh networks. In general, the traffic grooming problem for mesh networks has to be considered in combination with RWA problem, which we call the GRWA problem.

Typically, the cost of a nation-wide optical network is dominated by optical transponders and optical amplifiers. If one assumes that the fiber routes are fixed, then the amplifier cost is constant, in which case one should concentrate on minimizing the number of transponders in the network. Multiplexing and switching costs should also be considered. However, under realistic assumptions of either a low-cost interconnect between multiplexing equipment and transport equipment, or integrated (long-reach) transponders on the multiplexing equipment (as is typical of SONET ADMs), the relative cost of the grooming switch fabric is negligible, and minimizing transponders is still the correct objective. In addition, the advent of Ultra Long-Haul transmission often permits optical pass-through at junction nodes, hence, requiring transponders only at the end of lightpaths.

In early work on the RWA problem (e.g., see [25, Chapter 8] and references therein), the issue of grooming has largely been ignored, i.e., it has been assumed that each traffic demand takes up an entire wavelength. The traffic grooming problem for mesh networks is only recently considered in [19, 32, 18]. In [19], an attempt is made at solving the general grooming problem by formulating it as a 0/1 multi-commodity network flow problem with the goal of minimizing the number of links used. Clearly, minimizing link-usage is equivalent to minimizing the number of transponders because each link represents a lightpath and each lightpath requires the appropriate transponders for terminations and processing of the terminated traffic. Unfortunately, the 0/1 multi-commodity network flow problem is NP-complete, and very few algorithms have been developed for the problem. We should also point out that the issue of wavelength assignment was not considered in [19]. In [32], the objective considered is either to maximize the network throughput or to minimize the connection-blocking probability, which are operational network-design problems. In [18], the problem of GRWA with the objective of minimizing the number of transponders in the network is considered. The problem is first formulated as an ILP problem. Unfortunately, the resulting ILP problem is usually very hard to solve computationally, in particular for large networks. To overcome this difficulty, a decomposition method was proposed that divides the GRWA problem into two smaller problems: the traffic grooming and routing (GR) problem and the wavelength assignment (WA) problem. In the GR problem, one only needs to consider how to groom and route traffic demands onto lightpaths (with the same objective of minimizing the number of transponders) and the issue of how to assign specific wavelengths to lightpaths can be ignored. Similar to the GRWA problem, the GR problem is again formulated as an ILP problem. The size of the GR ILP problem is much smaller than its corresponding GRWA ILP problem. Furthermore, one can significantly improve the computational efficiency for the GR ILP problem by relaxing some of its integer constraints, which usually leads to near-optimal solutions for the GR problem. Once the GR problem is solved, one can then consider the WA problem with the goal of deriving a feasible wavelength assignment solution, that in many cases is quite easy to obtain.

11.6 Grooming in IP Networks

In future IP networks, SONET ADMs may no longer be needed to multiplex traffic onto wavelengths. Instead, future IP networks will involve routers that are connected via wavelengths using WDM cross-connects as shown in Figure 11.6a. Since the SONET multiplexers have been eliminated, the function of multiplexing traffic onto wavelengths has now been passed onto the IP routers. Unless optical bypass is intelligently employed, with the new architecture, all of the traffic on all fiber and on all wavelengths (which amounts to multiple Tera-bits) will now have to be processed at every IP router. Routers of this size and capacity far exceed any near-term prospects; and even when such routers could be built, they are likely to be very costly. This situation can be alleviated through the use of a WDM cross-connect to provide optical bypass as shown in Figure 11.6b. In order to achieve maximum efficiencies, one would need to bundle traffic onto wavelengths so that the number of wavelengths that have to be processed at each router is minimized. This objective results in both reducing the number of ports needed on the routers (one per wavelength add/dropped at the router) as well as reducing the total switching capacity of the router

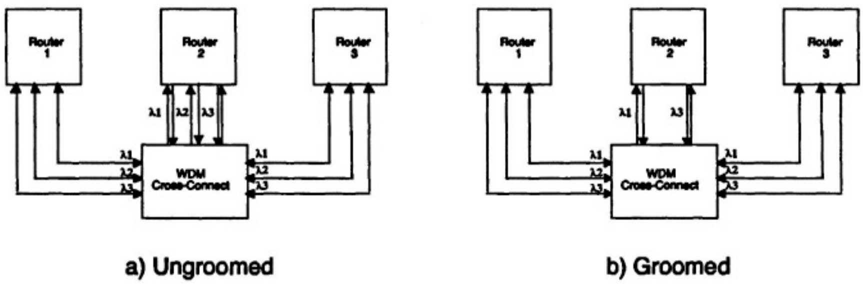

Figure 11.5. Grooming in an IP/WDM architecture.

This problem is similar to that of grooming of SONET streams described earlier. However, a number of important differences arise when considering the grooming of router traffic. First, unlike SONET networks, that are typically arranged in a ring topology, IP networks are arranged in a more general topology and hence the earlier grooming results cannot be applied directly. Second, SONET circuits are typically provisioned well in advance and remain for very long periods of time. As a result, in the case of a SONET network, the traffic grooming problem can be solved in advance, and network equipment can be laid-out accordingly. Most previous work on grooming for SONET rings considered particular traffic patterns (typically uniform traffic) for which a solution to the grooming problem was obtained. In the case of an IP network, not only is a uniform traffic pattern inappropriate, but also the traffic patterns are highly dynamic and hence a static solution would not be of much use.

11.7 The Impact of Tunable Transceivers

Here we consider the benefits of tunability in reducing electronic port counts in WDM/TDM networks (TDM stands for time division multiplexing). For a given traffic demand, we consider the design of networks that use the minimum number of tunable ports, where a tunable port refers to the combination of a tunable optical transceiver and an electronic port. Consider a network with N nodes. On each wavelength in the network, up to g low-rate circuits can be time division multiplexed, where g is the traffic granularity. A static traffic requirement for the network is given by an $N \times N$ matrix $[m_{i,j}]_{N \times N}$, where $m_{i,j}$ is the number of circuits required from node i to node j. Each node in the network is assumed to have a set of tunable ports, where each port includes a tunable optical transmitter and a tunable optical receiver. To illustrate the potential advantages of tunability, consider the following simple example of a unidirectional ring with $N = 4$, $g = 3$, and $m_{i,j} = 1$ for all i, j. In this case, the minimum number of wavelengths is 2, and there is a total of $N(N-1) = 12$ circuits that need to be assigned to the wavelengths. With $g = 3$, as many as 6 circuits can be assigned to each wavelength; this can be accomplished by assigning both circuits for each duplex connection to same time-slot. The traffic demand can then be supported by finding an assignment of each duplex connection to one of the g time-slots in the TDM frame, on one of the wavelengths in the ring. Without the possibility of tunable transceivers, the assignment of circuits to wavelengths corresponds to the standard traffic grooming problem considered so far, for which the optimal grooming solution is given in Table 11.5.

Table 11.5. **An optimal traffic assignment for fixed tuned transceivers.**

	λ_1	λ_2
Slot 1	(1-2)	(2-3)
Slot 2	(1-3)	(2-4)
Slot 3	(1-4)	(3-4)

Table 11.6. **Optimal traffic assignment with tunable transceivers.**

	λ_1	λ_2
Slot 1	(1-2)	(3-4)
Slot 2	(1-3)	(2-4)
Slot 3	(1-4)	(2-3)

However, it was shown in [4] that using tunable transceivers can help reduce the number of transceivers significantly. For example, consider the traffic assignment given above. Notice that node 3 only transmits and receives one wavelength at any given time (i.e., wavelength 2 in slot 1, wavelength 1 in slot 2 and wavelength 2 in slot 3). Hence if node 3 were equipped with a tunable transceiver, it would only need one transceiver rather than 2 and a total of 6 transceivers would be required. In the above assignment of circuits to slots, nodes 2 and 4 must transmit on both wavelengths in the same slot and hence must each be equipped with two transceivers. Alternatively, a more clever assignment, shown in Table 11.6, requires each node to transmit only on one wavelength during each slot and hence each node need only be equipped with a single tunable transceiver.

In this example, we show that the number of transceivers can be reduced from 7 to 4 by proper slot assignment. In this case, the optimal assignment can be found by inspection; however in larger networks this may be a non-trivial combinatorial problem. In fact, it was shown in [4] that in general the optimal assignment problem with tunable transceivers is NP-complete. The approach in [4] transforms the traffic grooming with tunable transceivers problem into a graph edge-coloring problem. While the graph coloring problem is known to be NP-complete, in many cases an exact solution can be found. For example, in the uniform traffic case, it was shown in [4] that with the use of tunable transceivers, each node can use the minimum number of transceivers, i.e., no more transceivers than the amount of traffic that it generates. This result hold for general traffic as well, as long as the number of wavelengths is not limited. With limited wavelengths, [4] provides algorithms that are very nearly optimal and significantly reduce the number of transceivers as compared to the fixed tuned transceivers case.

11.8 Summary

In this article, we attempted to expose the reader to various aspects of the traffic grooming problem. For a more comprehensive survey of the grooming literature the reader is referred to [9]. We start with a discussion of the static traffic grooming problem. The static problem, at this point is rather well understood. In the most general case, the problem can be formulated as an ILP and solved using various heuristics. However, many aspects of traffic grooming remain largely unexplored. Those include the problem of grooming of stochastic traffic, as well as grooming traffic with tunable transceivers [4]. The latter problem begins to expose a fundamental aspect of optical networking, whereby through the use of optical time division multiplexing (TDM) techniques, electronic processing, both in the form of switching and line terminal processing, can be drastically reduced in the network.

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