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# Design and operation of optical WDM networks with many-to-many traffic grooming

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**Design and operation of optical WDM networks with many-to-many traffic grooming**

by

Mohammad Saleh

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of  
DOCTOR OF PHILOSOPHY

Major: Computer Engineering

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Ames, Iowa

2011

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## DEDICATION

I would like to dedicate this thesis to my parents, wife, and daughter.

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## ABSTRACT

A large number of network applications today allow several users to interact together using the *many-to-many* service mode. In many-to-many communication, also referred to as group communication, a session consists of a group of users (we refer to them as *members*), where each member transmits its traffic to all other members in the same group. This dissertation addresses the problem of many-to-many traffic grooming in optical WDM mesh networks. In this problem, a set of many-to-many session requests, each with an arbitrary sub-wavelength traffic demand, are given and the objective is to provision the sessions on the optical WDM network with the minimum network cost. The cost of an optical WDM network is dominated by the cost of higher layer electronic ports (we refer to them as *transceivers*). Therefore, our objective is to minimize the total number of transceivers used, while also keeping the number of wavelengths used low, which is an NP-complete problem.

Based on different optical WDM node architectures, we propose four different WDM networks for many-to-many traffic grooming. One is the non-splitting opaque network, where the nodes are opaque and do not support optical splitting. In this network, a lightpath can only span a single physical link. Another one is the non-splitting transparent network, where the nodes are transparent but do not support optical splitting. In this network, a lightpath may span multiple physical links. The last two networks are the splitting hubbed and the splitting all-optical networks, where the nodes are transparent and support optical splitting. In these two networks, lightpaths and light-trees that may span multiple physical links are supported. In the splitting hubbed network, all members in a many-to-many session transmit their traffic to a designated hub node chosen from the set of nodes in the network. Using the technique of *network coding*, the hub then linearly combines the traffic units received together with its own

traffic units (if it is a member) and sends back to the members a set of linear combinations using light-tree(s). In the splitting all-optical network, each member in a many-to-many session transmits its traffic directly to all other members in the same session using a light-tree.

In this dissertation, we introduce the following contributions for the static many-to-many traffic grooming problem. First, we obtain the optimal solution for the problem in each of the proposed WDM networks using Mixed Integer Linear Program (MILP) formulations. Second, based on observations from the optimal solutions in two of the networks, we restrict the solution space of the corresponding MILPs to obtain near-optimal solutions in a much shorter time. Third, we introduce heuristic algorithms for the many-to-many traffic grooming problem in each of the four WDM networks. A comprehensive comparison between the four networks reveals that each of the networks is the most cost-effective choice for a certain range of traffic granularities. Fourth, we derive lower and upper bounds on the number of transceivers needed and also develop two novel approximation algorithms for one of the networks. For the case of the dynamic many-to-many traffic grooming problem, we introduce online provisioning algorithms for three of the networks with the objective of minimizing blocking probability of arriving sessions.

## CHAPTER 1. OVERVIEW

### 1.1 Introduction

In wavelength routing networks, using wavelength division multiplexing (WDM), the bandwidth of a fiber is divided into multiple disjoint optical channels (wavelengths). Currently, it is feasible to have hundreds of wavelengths, each operating at 10 to 40 Gbps, per fiber, and very soon 100 Gbps speeds will be commercially available. Bandwidth requirements of user sessions, however, are usually of sub-wavelength granularities. For example, an MPEG compressed HDTV channel requires less than 20 Mbps of bandwidth. In order to reduce this huge bandwidth gap, *traffic grooming* was introduced to allow a number of sessions with sub-wavelength granularities to share the bandwidth of a wavelength channel. In addition to determining the virtual topology and the routing and wavelength assignment of each of the wavelength channels, the traffic grooming problem deals with the intelligent assignment of sub-wavelength traffic demands onto the existing wavelength channels.

Early internet applications such as TELNET and FTP are characterized as unicast or "one-to-one". A large portion of network applications today, however, are of the multipoint type. For example, video distribution and file distribution are examples of multicast or "one-to-many" applications, while resource discovery and data collection are examples of many-to-one or "inverse multicasting" applications. Recently, another set of multipoint network applications has emerged which includes multimedia conferencing, e-science applications, distance learning, distributed simulations, and collaborative processing (1). In these applications, each of the participating entities both contributes and receives information to and from the other entities in the same communication session, and therefore characterized as "many-to-many". In many-to-many communication, also referred to as group communication (2), a session consists of a



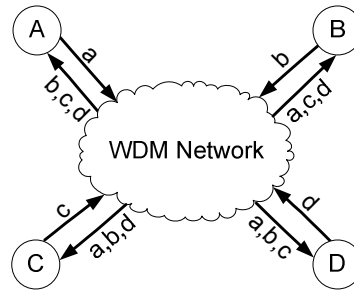


Figure 1.1 A many-to-many session with members  $\{A, B, C, D\}$  each with traffic denoted as  $a, b, c$  and  $d$ , respectively.

group of users (we refer to them as *members*), where each member transmits its traffic to all other members in the same group (see Fig. 1.1).

In order to effectively support many-to-many communication, nodes in a WDM network must be able to duplicate incoming traffic into multiple copies, each going to a different output port. Two main node architectures were proposed in the literature to implement this functionality. In the first one, nodes can only duplicate an incoming optical signal by applying optical-electronic-optical (*O/E/O*) conversion and duplication takes place in the electronic domain. In the second one, nodes are capable of splitting the incoming optical signal (using *optical splitters*) into multiple copies without any *O/E/O* conversion. Therefore, in this node architecture, traffic duplication can take place in both the electronic and the optical domains. Note that networks with the first type of nodes support only lightpaths, while networks with the second type of nodes support both lightpaths and *light-trees* (3).

The cost of an optical WDM network is dominated by the cost of higher layer electronic ports such as IP router ports, MPLS Label Switching Router (LSR) ports, and SONET ADM ports (we will refer to these ports as *transceivers*). A transceiver is needed for each initiation or termination of an optical channel. For example, a lightpath requires two transceivers while a light-tree with  $N$  endpoints requires  $N$  transceivers. Therefore, most of the studies on traffic grooming focus on minimizing the total number of transceivers used ( $R$ ). Note that associated with each electronic port that terminates or originates an optical channel are optical transceivers for transmitting and receiving the optical signal. Therefore, the cost of a transceiver includes both the cost of the electronic port and the cost of the associated optical

transceivers.

The rest of the chapter is organized as follows. In Section 1.2, we formally define the many-to-many traffic grooming problem in optical WDM mesh networks. In Section 1.3, we introduce the WDM node architectures and the proposed WDM networks for many-to-many traffic grooming, while in Section 1.4, we introduce the network model. In Section 1.5, we introduce the major contributions of this thesis, while in Section 1.6, we show the organization of the thesis.

## 1.2 The many-to-many traffic grooming problem

The traffic grooming problem even with unicast traffic and on simple topologies has been shown to be NP-complete by reduction from the bin packing problem (4). Furthermore, it was shown that on simple topologies where the routing and wavelength assignment can be done in polynomial time, the traffic grooming problem remains NP-complete (9). Most of the early work on traffic grooming has dealt with unicast traffic. Since a large portion of network applications today are of the multipoint type, many of the recent studies on traffic grooming has focused on multicast and many-to-one traffic types. In this work, we address the problem of many-to-many traffic grooming in optical WDM mesh networks, which we define as follows. Given an arbitrary optical WDM network topology, number of wavelengths per fiber, grooming factor, and a set of many-to-many session requests each with an arbitrary sub-wavelength traffic demand, determine the following:

1. What optical channels (lightpaths and light-trees) to establish and how to route and groom each of the sub-wavelength many-to-many traffic demands on these optical channels; This is known as the *virtual topology and traffic routing* (VTTR) problem.
2. How to route and assign a wavelength to each of the optical channels on the optical WDM network; This is known as the *routing and wavelength assignment* (RWA) problem.

The objective is usually to minimize the total number of transceivers used ( $R$ ). As indicated earlier, the traffic grooming problem even with unicast traffic and on simple topologies has been

proven to be NP-Complete (4). Furthermore, each of the two problems above is considered hard on general topologies. Although solving each problem independently is a more tractable approach than solving them combined, it will not guarantee an optimal solution. To guarantee an optimal solution, the two problems must be jointly considered. Although the main objective is to minimize the total number of transceivers used ( $R$ ), we are also interested in keeping the number of wavelengths used ( $W$ ) low since it also adds to the overall network cost.

### 1.3 WDM node architectures and the proposed WDM networks

Designing optical WDM networks is greatly influenced by the architecture of the optical node. The following are the optical node architectures that we consider:

- 1) *Opaque Node Architecture*: All incoming traffic must undergo optical-to-electronic ( $O/E$ ) conversion even if the traffic is not intended for the node. Transit traffic is switched in the electronic domain and then converted back to the optical domain for the next transmission.
- 2) *Transparent without Optical Splitting Node Architecture*: Incoming traffic not intended for the node may be switched in the optical domain without any  $O/E$  conversion. If the incoming traffic, however, is intended for multiple recipients or it needs to be groomed with other traffic, then  $O/E$  conversion is needed since traffic duplication and traffic grooming can only take place in the electronic domain.
- 3) *Transparent with Optical Splitting Node Architecture*: This is the same as transparent without optical splitting, except that multiple copies of the incoming traffic can be generated in the optical domain (using *optical splitters*) without any  $O/E$  conversion.

Based on these node architectures, we propose the following four WDM networks for many-to-many traffic grooming.

**1. Non-Splitting Opaque WDM (NSOWDM) Network:** In this network, all the nodes are opaque and therefore it supports lightpaths that can only span a single physical link. A lightpath may groom traffic from different sessions and traffic from different members within the same session. This network is efficient in terms of wavelength utilization, but has a relatively high transceiver cost. It will be shown that this network is suitable and cost-effective

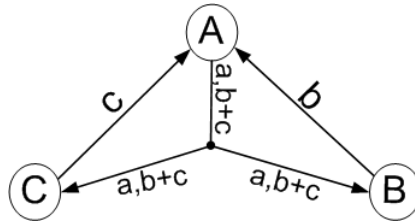


Figure 1.2 Provisioning of a many-to-many session with a set of members  $\{A, B, C\}$  each with traffic denoted as  $a, b$  and  $c$ , respectively in a SHWDM network (hub = A).

for traffic granularities that are relatively low (e.g., less than one-quarter of the capacity of a wavelength).

**2. Non-Splitting Transparent WDM (NSTWDM) Network:** In this network, all the nodes are transparent without optical splitting and therefore it supports lightpaths that may span multiple physical links. A lightpath may groom traffic from different sessions and traffic from different members within the same session. Note that the NSOWDM network is a special case of the NSTWDM network and therefore NSOWDM networks always require at least the same number of lightpaths as NSTWDM networks. However, due to the wavelength continuity constraint, NSTWDM networks generally consume more wavelengths than NSOWDM networks. It will be shown that NSTWDM networks are also suitable and cost-effective for low traffic granularities.

**3. Splitting Hubbed WDM (SHWDM) Network:** In this network, all the nodes are transparent with optical splitting and therefore it supports lightpaths and light-trees that may span multiple physical links. Each many-to-many session (with  $N$  members) has a designated hub node chosen from the set of nodes in the network including the members themselves. All the  $N$  members besides the hub transmit their traffic to the hub through direct lightpaths (upstream traffic). Using the new technique of *network coding* (40), the hub then linearly combines the traffic units received (together with its own traffic units if it is a member) to generate  $N - 1$  linearly independent combinations. These combinations must also be linearly independent from each of the original traffic units received from the members. Afterwards, the  $N - 1$  combinations are groomed and delivered back to the members using light-tree(s)

(downstream traffic), see Fig. 1.2. Each of the members will be able to recover the original traffic units transmitted by the other members in the same session by linearly combining its own traffic units with the received combinations (i.e., solving  $N$  linearly independent combinations).

For simplicity, we assume that all members in a many-to-many session have the same traffic demand. This assumption is needed to facilitate network coding at the hub node by linearly combining equally sized data units. We also assume that the linear combinations are performed using coefficients taken from a field of size two (i.e., addition modulo two or bitwise XOR). To perform network coding at the hub node, we may need to buffer traffic units that arrive early until all the traffic units arrive from the members. Using Next Generation SONET, multiservice provisioning platform (MSPP) equipment allows up to 128ms differential delay between different traffic streams.

Since light-trees are generally less efficient than lightpaths in packing and grooming low granularity traffic, this network has less grooming capabilities than the previous two networks. It will be shown that this network is suitable and cost-effective for traffic granularities that are around half of the capacity of a wavelength.

The use of network coding in SHWDM networks reduces the downstream traffic for each session (with  $N$  members) from  $N$  to  $N - 1$  data units. This has a direct impact on reducing the number of required light-trees, and hence the number of transceivers.

**4. Splitting All-Optical WDM (SAOWDM) Network:** In this network, all the nodes are transparent with optical splitting. Each member in a many-to-many session transmits its traffic directly to all other members in the same session using a light-tree (see Fig. 1.3). Note that no traffic grooming is performed in this network, and therefore it is suitable and cost-effective for traffic granularities that are close to the full capacity of a wavelength.

A major contribution of this dissertation is a comprehensive study of the many-to-many traffic grooming problem on all the four networks proposed above, and a comprehensive comparison which reveals that each of the networks is the most cost-effective choice for a certain range of traffic granularities. The optimal strategies for grooming many-to-many sessions on each of the four networks can be different. We illustrate this using the example shown in Fig.

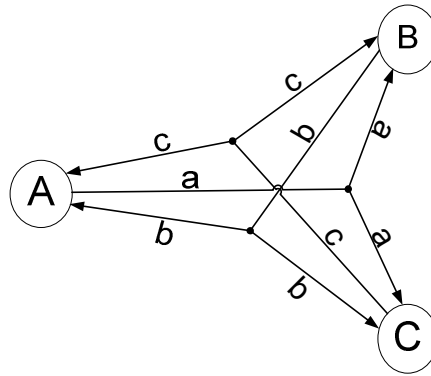


Figure 1.3 (Provisioning of a many-to-many session with a set of members  $\{A, B, C\}$  each with traffic denoted as  $a, b$  and  $c$ , respectively in a SAOWDM network.

1.4 which compares NSTWDM networks and SHWDM networks in terms of the number of transceivers required ( $R$ ). Nodes  $A, B, C$  and  $D$  are members of a many-to-many session. Each of the members needs to transmit one unit of traffic denoted as  $a, b, c$  and  $d$ , respectively, to the other three members. For the sake of this example, we assume that the capacity of a wavelength channel (grooming factor) is four units of traffic. In the NSTWDM network case, Figure 1.4.(a) illustrates the optimal provisioning of the session which requires four lightpaths (eight transceivers). In the SHWDM network case, Figure 1.4.(b) illustrates the optimal provisioning of the session ( $hub = B$ ) which requires three lightpaths and one light-tree (ten transceivers). Note that each of the members  $A, C$  and  $D$  will be able to recover the original traffic units by performing bitwise XOR operations between  $a + c, a + d$  and their own traffic unit. For example, node  $C$  will perform XOR between  $a + c$  and  $c$  to recover  $a$  and then perform XOR between  $a + d$  and  $a$  to recover  $d$ . Note that the hub  $B$  did not combine its own traffic unit  $b$  with other traffic, however it could, for example, combine  $b$  with  $c$  and send  $b + c$  instead of  $b$ . In either case, the solution requires a total of ten transceivers, which costs two more transceivers than the NSTWDM network case. On the other hand, if  $a, b, c$  and  $d$  were two units of traffic instead of one, then the optimal provisioning in the NSTWDM network case is shown in Figure 1.4.(c), which requires eight lightpaths (16 transceivers). However, in the SHWDM network case ( $hub = B$ ), the optimal provisioning requires three lightpaths and two

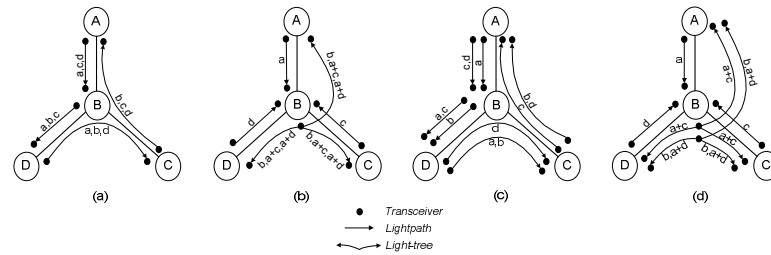


Figure 1.4 Provisioning of a many-to-many session with a set of members  $\{A, B, C, D\}$  each with traffic denoted as  $a, b, c$  and  $d$ , respectively (grooming factor=4) in: (a) a NSTWDM network case where  $a, b, c$  and  $d$  are one unit of traffic, (b) a SHWDM network case where  $a, b, c$  and  $d$  are one unit of traffic ( $hub = B$ ), (c) a NSTWDM network case where  $a, b, c$  and  $d$  are two units of traffic, (d) a SHWDM network case where  $a, b, c$  and  $d$  are two units of traffic ( $hub = B$ ).

light-trees (14 transceivers) as shown in Figure 1.4.(d). This saves two transceivers compared to the NSTWDM network case.

We can observe from this example that NSTWDM networks are more cost-effective for low traffic granularities, while SHWDM networks are more cost-effective for high traffic granularities. Although the above example only compares NSTWDM and SHWDM networks and only considers the cost  $R$ , we will conduct in this work an extensive cost comparison between the four networks on both the costs  $R$  and  $W$  and show when each of the networks is the most cost-effective choice for many-to-many traffic grooming.

## 1.4 Model

In this section, we introduce the network model that we consider for many-to-many traffic grooming. In this model, we view the network at three different layers:

1) *The Physical Layer*: This layer includes the fiber network consisting of optical nodes and fiber links. The number of wavelengths per fiber is the same along all fibers, and the capacity of a wavelength (i.e., the grooming factor) is also the same among all wavelengths. We assume that any two nodes in the network are connected by at most one physical link (two unidirectional fibers in opposite directions). In our problem, we assume that the physical

optical WDM network is given, including optical amplifiers and/or *O/E/O* regenerators, if any.

2) *The Optical Layer*: This layer includes the optical channels (lightpaths and light-trees) that are established on the fiber network. A lightpath in a NSOWDM network can only traverse a single fiber link, while in a NSTWDM network it may traverse multiple fiber links. We assume that intermediate nodes have no wavelength conversion capability. This constrains a lightpath to use the same wavelength on all the fiber links it traverses. A light-tree in a SHWDM network is always rooted at the hub of a session, which may or may not be one of the members of that session. The leaves of the light-tree are the members (or the remaining members if the hub is a member) of that session. Accordingly, a light-tree in a SHWDM network is associated with a particular session, e.g, when we say "light-tree for session  $s_k$ " we mean a light-tree that is rooted at the hub of  $s_k$  and its leaves are the members (or the remaining members) of  $s_k$ . Consider, for example, a many-to-many session  $s_0$  with a set of members  $m_{s_0} = \{A, B, C, D, E\}$ , and let us assume that  $hub(s_0) = A$ . A "light-tree for  $s_0$ " in a SHWDM network is a light-tree that is rooted at  $A$  and its leaves are  $\{B, C, D, E\}$ . A light-tree in a SAOWDM network is always rooted at one of the members in a session and its leaves are the remaining members of that session (see Fig. 1.3). Similar to a lightpath, a light-tree must use the same wavelength on all the fiber links it traverses.

3) *The Session Layer*: This layer includes the routing and the grooming of the many-to-many traffic demands on the optical channels. Lightpaths and light-trees may groom traffic from different sessions and traffic from different members within the same session. In NSOWDM and NSTWDM networks, the traffic originating from a member may traverse multiple lightpaths to reach any other member in the same session. In SAOWDM networks, each member in a many-to-many session transmits its traffic directly to all other members in the same session using a light-tree (no grooming is performed). To provision and groom many-to-many sessions in SHWDM networks, we must determine the following:

- *hub selection*: selecting the hub node for each session from the set of nodes in the network.
- *members-to-hub journey*: determining how to route the traffic from each of the members



to the hub. The traffic originating from a member may traverse multiple lightpaths to reach the hub.

- *hub-to-members journey*: determining how to route the linear combinations of the original traffic units from the hub node back to the members. This traffic is either delivered through light-tree(s) for the corresponding session or through light-tree(s) for other sessions. For example, consider the 4-node network shown in Fig. 1.4 with three many-to-many session requests  $s_0$ ,  $s_1$  and  $s_2$  each with a set of members  $m_{s_0} = \{A, B, C, D\}$ ,  $m_{s_1} = \{A, B, C\}$  and  $m_{s_2} = \{A, B, D\}$ , respectively. Let us assume that  $hub(s_0) = hub(s_1) = hub(s_2) = B$ , then one possible routing of the hub-to-members journey of the three sessions is to establish a light-tree for  $s_1$  ( $B \rightarrow \{A, C\}$ ) and a light-tree for  $s_2$  ( $B \rightarrow \{A, D\}$ ) and to route the hub-to-members journey of  $s_0$  on the two established light-trees (assuming that each of the light-trees has enough capacity to accommodate session  $s_0$  traffic units). This example also shows the significance of the hub selection since the hub-to-members journey of a session cannot be routed on a light-tree for another session unless the two sessions share the same hub node.

## 1.5 Research Contributions

The objective of this work is to study the many-to-many traffic grooming problem in four different optical WDM network architectures. The many-to-many traffic grooming problem is a new research problem that has not been addressed before. First, we formulate the problem in each of the WDM networks as a Mixed Integer Linear Program (MILP). Then, based on observations from the optimal solution in NSTWDM and SHWDM networks, we restrict the solution space of the corresponding MILPs to obtain near-optimal solutions in a much shorter time. Afterwards, for NSOWDM and NSTWDM networks, we introduce *lightpath cycles* (a formal definition will be given later) as the optimal virtual topology for single and multiple many-to-many sessions in special cases. Based on lightpath cycles, efficient near-optimal heuristic algorithms are developed for the general case of the many-to-many traffic grooming problem. For the SHWDM network, we develop an efficient heuristic algorithm that combines optical

splitting and network coding to provision many-to-many sessions. A comprehensive comparison between the four networks reveals that each of the networks is the most cost-effective choice for a certain range of traffic granularities. For example, the comparison reveals that NSOWDM and NSTWDM networks are the most cost-effective for low traffic granularities, SAOWDM networks are the most cost-effective for high traffic granularities, and SHWDM networks are the most cost-effective for traffic granularities that lie in the middle. Another contribution of this work is the derivation of lower and upper bounds on the number of transceivers needed and the development of two novel approximation algorithms in the NSTWDM network case. A final contribution of this dissertation is the development of online provisioning algorithms for the dynamic many-to-many traffic grooming problem in NSTWDM, SHWDM, and SAOWDM networks.

## 1.6 Thesis Organization

The rest of the thesis is organized as follows. In Chapter 2, we review and discuss work in the literature that is related to static and dynamic traffic grooming in optical WDM networks. In Chapter 3, we consider the optimal design of each of the four WDM networks for many-to-many traffic grooming by formulating Mixed Integer Linear Programs (MILPs). In Chapter 4, we introduce heuristic solutions for the many-to-many traffic grooming in each of the four WDM networks. We first restrict the solution space of the MILPs for NSTWDM and SHWDM networks to obtain near-optimal solutions in a much shorter time and then introduce efficient near-optimal heuristic algorithms for the four WDM networks. In Chapter 5, we derive lower and upper bounds on the number of transceivers required and then develop two novel approximation algorithms in the NSTWDM network case. In Chapter 6, we address the dynamic many-to-many traffic grooming problem in optical WDM mesh networks, where we introduce online provisioning algorithms in NSTWDM, SHWDM, and SAOWDM networks. Finally, in Chapter 7, we conclude the thesis and outline a few directions for our future work.

## CHAPTER 2. LITERATURE REVIEW

In this chapter, we review and discuss the literature on traffic grooming in optical WDM networks. The work on traffic grooming can be classified in a number of ways. First, it may be classified based on the type of traffic; whether it is unicast, multicast, many-to-one, or many-to-many traffic. It can also be classified based on whether the traffic is given in advance (i.e., static traffic grooming) or it is not given in advance and it arrives dynamically (i.e., dynamic traffic grooming). Another classification is based on the topology of the optical WDM network, i.e., whether it is a unidirectional ring, bidirectional ring, or a general mesh topology. In this chapter, we classify the traffic grooming literature based on the traffic type studied; namely unicast traffic grooming, multicast traffic grooming, many-to-one traffic grooming, and many-to-many traffic grooming. Moreover, in each of these classifications, we further classify the work based on whether the traffic is static or dynamic and based on the topology of the optical WDM network. Table 2.1 summarizes the studies related to traffic grooming based on this classification. In the following sections, we review each of the studies listed in Table 2.1.

### 2.1 Unicast Traffic Grooming

Traffic grooming has been extensively studied for unicast traffic (4)-(19). Some of the studies were restricted to ring topologies (4)-(8), while others were for general mesh topologies (9)-(19). In (5), the authors addressed the traffic grooming problem on a number of WDM ring architectures with the objective of minimizing the overall network cost. They conducted a comprehensive comparison between the WDM ring architectures based on a number of cost metrics including the number of wavelengths, transceivers cost, and the maximum number of

Table 2.1 Classification of work related to traffic grooming

Traffic Type	Static	Dynamic	Ring	Mesh
Unicast	(4)-(15)	(16)-(19)	(4)-(8)	(9)-(19)
Multicast	(20)-(24), (30)-(31)	(26)-(30)	(20)-(21)	(22)-(31)
Many-to-one	(25)	-	-	(25)
Many-to-Many	(32)-(38)	(39)	(32)-(33)	(35)-(38)

hops. In (6), the authors proposed optimal and near-optimal algorithms for traffic grooming in SONET WDM rings with the objective of minimizing the number of wavelengths and SONET ADMs. Their work covered both unidirectional and bidirectional WDM rings with both uniform and nonuniform traffic. They showed that the performance of the proposed algorithms either matches or is very close to a lower bound they derived in the paper. In (7), the authors studied the grooming of arbitrary traffic in WDM bidirectional line-switched rings (BLSRs) with the objective of minimizing the cost of add-drop multiplexers (ADMs). They considered four versions of the problem based on whether routing of traffic streams is predetermined and based on whether traffic bifurcation is allowed at intermediate nodes. They derived general lower bounds and developed a number of approximation algorithms. In (8), the authors addressed the grooming of low-speed traffic into high-speed lightpaths on a number of SONET optical ring architectures, including UPSR and BLSR rings. They also considered the use of back-to-back connections between SONET ADMs to reduce the overall cost, and the use of different ring speeds (OC-48 and OC-12). Assuming a uniform traffic model, they derived lower and upper bounds on the number of ADMs needed.

In (13), the authors addressed the traffic grooming problem in an optical WDM mesh network. They first introduced a mathematical ILP formulation to obtain the optimal solution and then developed a number of heuristic algorithms that maximize single-hop traffic and resource utilization. In (10), the authors provided a decomposition method that divides the traffic grooming problem into two smaller problems and then solved each problem independently. The first problem is the traffic grooming and routing problem where they introduced an ILP formulation and then relaxed the integer constraints to obtain approximate solutions. The second problem is the wavelength assignment problem where they proposed an algorithm

that finds a feasible wavelength assignment under certain conditions. In (9), the authors addressed the traffic grooming problem in optical WDM path, star and tree networks. They introduced several results on the complexity of the traffic grooming problem in each of the network topologies. They also derived lower and upper bounds and developed practical grooming algorithms and heuristics. In (12), the authors showed that the traffic grooming problem is APX-hard, which means that the optimum cannot be approximated arbitrarily closely. They also proposed approximation algorithms for minimizing the total equipment cost and for minimizing the lightpath count. In (15), the authors provided a hierarchical framework for traffic grooming in an optical WDM mesh network. At the first level of the hierarchy, they divided the network into clusters each with a designated node as the hub for grooming intra-cluster traffic. At the second level, the hubs form another cluster to groom inter-cluster traffic. For an account of recent advances in unicast traffic grooming, the reader is referred to (14), (11).

All of the references (4)-(15) have dealt with the static traffic grooming problem where traffic demands are known in advance. In (16)-(19), the dynamic traffic grooming problem where sessions arrive and leave the network dynamically was considered. In (16), the authors proposed a framework (called MICRON) for dynamic sub-wavelength connection establishment in optical WDM networks with heterogeneous switching architectures. The MICRON framework may be easily implemented with simple traffic engineering extensions to the already existing routing protocols in wide-area networks. In (17), the authors developed an analytical model to compute blocking probabilities in WDM mesh networks with dynamic traffic grooming. Their model allows heterogeneous data rates for sub-wavelength connections, arbitrary alternate routing in both logical and physical topologies, and arbitrary wavelength conversion. In (18), the authors proposed an auxiliary graph model for traffic grooming in heterogeneous WDM mesh networks. Their model can achieve various objectives using different grooming policies, while taking into account various constraints such as transceivers, wavelengths, wavelength-conversion capabilities, and grooming capabilities. They also developed an integrated traffic grooming algorithm that jointly solves the traffic grooming subproblems. In (19), the authors introduced a methodology for dynamic routing of fractional-wavelength traffic demands in

optical WDM grooming networks. They evaluated the performance of a number of routing algorithms including shortest-widest path, widest-shortest path, and available shortest path routing algorithms.

## 2.2 Multicast Traffic Grooming

Traffic grooming has also been considered for multicast traffic (20)-(31). Some of the studies were restricted to ring topologies (20)-(21), while others were for general mesh topologies (22)-(31). In (20), the authors addressed the multicast traffic grooming problem in metropolitan optical WDM ring networks with the objective of minimizing electronic copying. They presented an ILP formulation to obtain the optimal solution and then developed a heuristic approach that consists of three phases: routing, circle construction, and grouping of circles. In (21), the authors studied the problem of grooming non-uniform multicast traffic in unidirectional SONET WDM rings with the objective of minimizing the number of wavelengths and SONET ADMs. They introduced a graph based heuristic and compared it to the multicast extension of the best known unicast traffic grooming heuristic in (6). They observed that their proposed heuristic requires fewer ADMs than the multicast extension of the unicast heuristic given in (6). The authors also derived a lower bound and compared it against some upper bounds to study the maximum penalty of not employing intelligent wavelength assignment and/or traffic grooming.

In (22), the authors addressed the static multicast traffic grooming problem in optical WDM mesh networks. Besides the general multicast scenario, they have also considered other interesting scenarios such as multicast with partial destination set reachability and multicast with traffic thinning. They provided MILP formulations to obtain the optimal solution and developed heuristic solutions. In (23), the authors considered the multicast traffic grooming problem in WDM mesh networks with sparse nodal light splitting capability with the objective of reducing the number of wavelengths used. In (24), the authors introduced a non-linear programming formulation as an analytical model for the multicast traffic grooming problem in a WDM mesh network with nodal light splitting capability. They also introduced three

heuristic algorithms: K-shortest path trees heuristic, grooming with rerouting the sessions heuristic, and grooming by computing overlapped trees heuristic.

All of the references (20)-(24) have dealt with the static multicast traffic grooming problem where traffic demands are given in advance. In (26), the authors considered online provisioning algorithms for dynamic multicast traffic grooming with the objective of maximizing resource utilization and minimizing blocking probability. The network model that they considered assumed a translucent node architecture. In (27)-(28), the authors considered the dynamic multicast traffic grooming problem in optical WDM mesh networks with the assumption that multicast sessions are provisioned using light-trees. They proposed four grooming approaches to accommodate arriving sessions: sequential single-hop provisioning, sequential multihop provisioning, hybrid provisioning and non-restricted sequential multihop provisioning. In the sequential approaches, existing light-trees and lightpaths were used to accommodate new sessions, and in the hybrid approach new light-trees and light-paths are created in addition to using the existing virtual topology. In (29), the authors addressed the online multicast traffic grooming problem in wavelength-routed WDM mesh networks with sparse grooming capabilities. They developed a multicast dynamic light-tree grooming algorithm (MDTGA) that can support multihop traffic grooming by taking advantage of light-trees. In their algorithm, a light-tree can be dropped, branched, and extended when a route is to be established for a new request; a light-tree can also be contracted when some branches carry no effective traffic after requests depart from the network. For an account of recent advances in static and dynamic multicast traffic grooming in optical WDM networks, the reader is referred to (30), (31) Chapter 14.

### 2.3 Many-to-one Traffic Grooming

In (25), the authors addressed the problem of many-to-one traffic grooming with traffic aggregation in optical WDM mesh networks with the objective of minimizing the number of wavelengths and SONET ADMs. They assumed that traffic streams from different sources but part of the same session and thus terminating at the same destination can be aggregated using

arbitrary but application dependent aggregation ratios. They obtained the optimal solution for the problem by formulating a mixed integer linear program (MILP) to an otherwise non-linear problem by exploiting the specifics of routing and aggregation sub-problems. They also introduced a dynamic programming style approach that builds the solution progressively as a heuristic solution. For a summary of recent advances in many-to-one traffic grooming, the reader is referred to (31) Chapter 14.

## 2.4 Many-to-Many Traffic Grooming

The many-to-many traffic grooming problem in optical WDM mesh networks is a new research problem that has not been addressed before. Aside from the work in this thesis and the resulted publications (35)-(39), only the work in (32)-(33) addressed the many-to-many traffic grooming problem in optical WDM ring networks. The authors used network coding to provision many-to-many traffic with the objective of minimizing the number of LTEs. They considered two types of unidirectional rings, namely, single-hub and unhubbed rings. They have shown, through numerical results, that network coding can reduce the network cost by 10-20% in single-hub rings and 1-5% in un-hubbed rings.



## CHAPTER 3. OPTIMAL DESIGN

In this chapter, we consider the optimal design of each of the WDM networks proposed in Chapter 1 for many-to-many traffic grooming. As stated in Chapter 1, the traffic grooming problem involves two smaller problems which must be jointly considered to guarantee an optimal solution. The first one is the *virtual topology and traffic routing* (VTTR) problem, and the second one is the *routing and wavelength assignment* (RWA) problem. We formulate the combined problem in each of the WDM networks as a Mixed Integer Linear Program (MILP). The input parameters used in the MILPs are shown in Table 3.1.

Regarding notation, we use  $p$  and  $q$  to refer to any two members in a many-to-many session, while we use  $h$  to refer to the hub of a session. Also, we use  $i$  and  $j$  to refer to the source and destination nodes of a lightpath, while we use  $m$  and  $n$  to refer to the end nodes of a fiber link. Finally, we use  $w$  to refer to wavelength number  $w$  where  $1 \leq w \leq W_{max}$ .

The rest of the chapter is organized as follows. In Sections 3.1, 3.2, 3.3, and 3.4, we formulate Mixed Integer Linear Programs (MILPs) for the many-to-many traffic grooming problem in NSOWDM, NSTWDM, SHWDM, and SAOWDM networks, respectively. In Section 3.5, we provide an illustrative numerical example from MILP solutions in each of the four networks. In Section 3.6, we summarize the chapter.

### 3.1 MILP Formulation for NSOWDM Networks

In NSOWDM networks, lightpaths are the only optical communication channels available to provision many-to-many sessions. A lightpath can only span a single physical link and it may groom traffic from different sessions and traffic from different members within the same session. The traffic originating from a member may traverse multiple lightpaths to reach any

Table 3.1 Input parameters

Symbol	Definition
$G(V, E)$	undirected graph with a set of nodes $V$ and a set of links $E$ which represents the physical topology of the WDM network. Each undirected link is composed of two unidirectional fibers in opposite directions.
$N$	number of nodes in the network ( $N =  V $ ).
$P_{mn}$	binary number equals to 1 if there is a fiber link from node $m$ to node $n$ ; otherwise it is set to 0 ( $P_{mn} = P_{nm}$ ).
$W_{max}$	number of wavelengths per fiber, which we set large enough to guarantee a feasible solution.
$g$	grooming factor (capacity of a wavelength channel in terms of the number of basic units of traffic).
$K$	number of many-to-many sessions.
$s_k$	many-to-many session number $k$ ( $1 \leq k \leq K$ ).
$m_{s_k}$	set of members in session $s_k$ ( $m_{s_k} \subseteq V$ ).
$B_l^{s_k}$	binary number equals to 1 if $l \in m_{s_k}$ ; otherwise it is set to 0.
$N_{s_k}$	number of members in session $s_k$ ; $N_{s_k} =  m_{s_k} $ .
$t_{s_k}$	number of basic units of traffic demanded by each member in session $s_k$ , where $1 \leq t_{s_k} \leq g$ .
$Q$	a large integer ( $Q \geq K \cdot  V $ ).

other member in the same session. Therefore, the many-to-many traffic grooming problem in NSOWDM networks is to determine: 1) how many lightpaths to establish on each physical link in the network, and 2) how to route and groom each of the sub-wavelength many-to-many traffic demands on these lightpaths. The objective is to minimize the total number of transceivers used. Note that there is no need for the RWA problem since a lightpath can only traverse a single physical link. In this section, we introduce an MILP formulation for the many-to-many traffic grooming problem in NSOWDM networks. The decision variables used in this MILP (which are only defined when  $P_{ij} = 1$  since it is a NSOWDM network) are shown in Table 3.2.

#### Objective Function:

$$\text{Minimize: } \sum_n R_n$$

#### Subject to:

*Number of Transceivers Constraints:*

The following constraint ensures that at the source and at the destination of each lightpath

Table 3.2 Decision variables for NSOWDM networks MILP which are only defined when  $P_{ij} = 1$

Symbol	Definition
$R_n$	number of transceivers at node $n$ .
$L_{ij}^w$	number of lightpaths from node $i$ to node $j$ on wavelength $w$ .
$L_{ij}$	number of lightpaths from node $i$ to node $j$ on all wavelengths; $L_{ij} = \sum_w L_{ij}^w$ .
$Z_{ij}^{s_k,p,q}$	binary number equals to 1 if the traffic stream originating from member $p \in m_{s_k}$ and destined to member $q \in m_{s_k}$ is routed on a lightpath from node $i$ to node $j$ ; otherwise it is set to 0 ( $p \neq q$ ).
$Y_{ij}^{s_k,p}$	binary number equals to 1 if a traffic stream originating from member $p \in m_{s_k}$ and destined to at least one other member in $m_{s_k}$ is routed on a lightpath from node $i$ to node $j$ ; otherwise it is set to 0.
$X_{ij}^{s_k}$	real number equals to the amount of traffic carried on lightpaths from node $i$ to node $j$ due to all members in $m_{s_k}$ .

there is a transceiver present.

$$R_i \geq \sum_{j:j \neq i} (L_{ij} + L_{ji}) \quad \forall i \quad (3.1)$$

*Session Level Constraint:*

The following is the traffic routing constraint between each pair of members in a many-to-many session. It ensures that the traffic originating from a member and destined to any other member in the same session may traverse multiple lightpaths.

$$\sum_{i:P_{ix}=1} Z_{ix}^{s_k,p,q} - \sum_{j:P_{xj}=1} Z_{xj}^{s_k,p,q} = \begin{cases} 1, & \text{if } x = q \\ -1, & \text{if } x = p \\ 0, & \text{otherwise} \end{cases} \quad \forall s_k, p, q \in m_{s_k}, x \in V \quad (3.2)$$

Constraints (3.3) and (3.4) together set the variable  $Y_{ij}^{s_k,p}$  as the logical disjunction of all the variables  $Z_{ij}^{s_k,p,q}$  for all values of  $q \in m_{s_k}$ ,  $q \neq p$ .

$$Y_{ij}^{s_k,p} \geq \sum_{q \in m_{s_k}} Z_{ij}^{s_k,p,q} / N_{s_k} \quad \forall s_k, p \in m_{s_k}, i, j : P_{ij} = 1 \quad (3.3)$$

$$Y_{ij}^{s_k,p} \leq \sum_{q \in m_{s_k}} Z_{ij}^{s_k,p,q} \quad \forall s_k, p \in m_{s_k}, i, j : P_{ij} = 1 \quad (3.4)$$

$Y_{ij}^{s_k,p}$  will be set to 1 if at least one of the traffic streams that originate from member  $p$  uses a lightpath from  $i$  to  $j$ . Note that when  $Y_{ij}^{s_k,p} = 1$ , then lightpaths from  $i$  to  $j$  carry the  $t_{s_k}$  traffic

units that originate from member  $p$ . The following constraint determines the total amount of traffic carried on lightpaths from  $i$  to  $j$  due to all members in session  $s_k$ .

$$X_{ij}^{s_k} = t_{s_k} \sum_{p \in m_{s_k}} Y_{ij}^{s_k,p} \quad \forall s_k, i, j : P_{ij} = 1 \quad (3.5)$$

The following constraints determine the total number of lightpaths needed on each physical link in the network.

$$L_{ij} \geq \left( \sum_{s_k} X_{ij}^{s_k} \right) / g \quad \forall i, j : P_{ij} = 1 \quad (3.6)$$

$$L_{ij} \leq W_{max} \quad \forall i, j : P_{ij} = 1 \quad (3.7)$$

### 3.2 MILP Formulation for NSTWDM Networks

In a NSTWDM network, a direct lightpath (that may span multiple physical links) can be established between any two nodes in the network. Therefore, the MILP formulation for the many-to-many traffic grooming problem in a NSTWDM network will be exactly the same as the MILP formulation introduced earlier for a NSOWDM network except the following changes. First, all the decision variables  $L_{ij}^w$ ,  $L_{ij}$ ,  $X_{ij}^{s_k}$ ,  $Z_{ij}^{s_k,p,q}$ ,  $Y_{ij}^{s_k,p}$  and the constraints that contain them are now defined for all values of  $i, j \in V$  ( $i \neq j$ ) and not just when  $P_{ij} = 1$ . Second, we have the following new decision variable:

$F_{mn}^{ij,w}$  binary number equals to 1 if there is a lightpath from node  $i$  to node  $j$  that uses fiber link  $mn$  on wavelength  $w$ ; otherwise it is set to 0.

Also, we have the following new set of constraints:

*Lightpath Level Constraints:*

The following constraint ensures that for each lightpath from node  $i$  to node  $j$  there is a corresponding physical path from  $i$  to  $j$  that uses the same wavelength on all the fiber links it traverses.

$$\sum_{m:P_{mx}=1} F_{mx}^{ij,w} - \sum_{n:P_{xn}=1} F_{xn}^{ij,w} = \begin{cases} L_{ij}^w, & \text{if } x = j \\ -L_{ij}^w, & \text{if } x = i \\ 0, & \text{otherwise} \end{cases} \quad \forall i, j, w, x \in V \quad (3.8)$$

The following constraint ensures that for any wavelength  $w$  on any fiber link  $mn$  no more than one lightpath can be present.

$$\sum_i \sum_j F_{mn}^{ij,w} \leq 1 \quad \forall w, m, n : P_{mn} = 1 \quad (3.9)$$

Note that the previous constraint (3.9) guarantees that the total number of lightpaths routed on any fiber link does not exceed  $W_{max}$ . Finally, constraint (3.7) is removed since the number of lightpaths between any pair of nodes in a NSTWDM network could exceed  $W_{max}$ .

### 3.3 MILP Formulation for SHWDM Networks

In this section, we introduce an MILP formulation for the many-to-many traffic grooming problem in a SHWDM network. First, we introduce the decision variables that are used in this MILP formulation. The variables  $R_n$ ,  $L_{ij}^w$ ,  $L_{ij}$ ,  $X_{ij}^{s_k}$  and  $F_{mn}^{ij,w}$  are defined exactly the same way as in the NSTWDM MILP and the new decision variables are shown in Table 3.3.

#### Objective Function:

$$\text{Minimize: } \sum_n R_n$$

#### Subject to:

*Number of Transceivers Constraints:*

The following constraint ensures that at the source and at the destination of each lightpath there is a transceiver present. Also, it ensures that at the root and at the leaves of each light-tree there is a transceiver present.

$$R_i \geq \sum_{j:j \neq i} (L_{ij} + L_{ji}) + \sum_{s_k} LT_{s_k} B_i^{s_k} + \sum_{s_k:i \notin m_{s_k}} A_i^{s_k} \quad \forall i \quad (3.10)$$

The first term counts all the lightpaths originating and terminating at node  $i$ . The second term counts all light-trees for sessions where node  $i$  is a member, while the third term counts all light-trees for sessions where node  $i$  is a hub but not a member. The nonlinear term  $A_i^{s_k}$  can be computed using the following set of linear constraints (together with the minimization in the objective function).

$$A_i^{s_k} \geq QI_i^{s_k} - Q + LT_{s_k} \quad \forall s_k, i \quad (3.11)$$

Table 3.3 Decision variables for SHWDM networks MILP

Symbol	Definition
$I_h^{s_k}$	binary number equals to 1 if node $h$ is the hub node for session $s_k$ ; otherwise it is set to 0.
$E_{s_l}^{s_k, h}$	binary number equals to 1 if sessions $s_k$ and $s_l$ share node $h$ as their hub node; otherwise it is set to 0.
$E_{s_l}^{s_k}$	binary number equals to 1 if sessions $s_k$ and $s_l$ share the same hub node; otherwise it is set to 0.
$D_{ij}^{s_k, p}$	binary number equals to 1 if the traffic stream originating from member $p \in m_{s_k}$ and destined to the hub of session $s_k$ is routed on a lightpath from node $i$ to node $j$ ; otherwise it is set to 0.
$R_{mn}^{s_k, p, w}$	binary number equals to 1 if there is a light-tree for session $s_k$ with root (hub of $s_k$ ) to leaf (member $p \in m_{s_k}$ ) path that uses fiber link $mn$ on wavelength $w$ ; otherwise it is set to 0.
$R_{mn}^{s_k, w}$	binary number equals to 1 if at least one of the root (hub of $s_k$ ) to leaf (member in $m_{s_k}$ ) paths of a light-tree for session $s_k$ uses fiber link $mn$ on wavelength $w$ ; otherwise it is set to 0.
$U_{s_l}^{s_k}$	binary number equals to 1 if session $s_k$ is routed on a light-tree for session $s_l$ ; otherwise it is set to 0.
$T_{s_l}^{s_k}$	real number equals to the amount of traffic carried on light-trees for session $s_l$ due to members in session $s_k$ .
$LT_{s_k}^w$	number of light-trees for session $s_k$ on wavelength $w$ .
$LT_{s_k}$	number of light-trees for session $s_k$ on all wavelengths; $LT_{s_k} = \sum_w LT_{s_k}^w$ .
$A_h^{s_k}$	non-negative real number equals to the product of $LT_{s_k}$ and $I_h^{s_k}$ .

$$A_i^{s_k} \leq LT_{s_k} \quad \forall s_k, i \quad (3.12)$$

Note that constraint (3.12) (the upper bound for  $A_i^{s_k}$ ) is not needed due to the minimization in the objective function; however, keeping it limits the search space for the MILP.

*Lightpath Level Constraint:*

This will be exactly the same as the lightpath level constraint (3.8) in the NSTWDM networks MILP.

*Light-tree Level Constraints:*

In this set of constraints, we visualize a light-tree for session  $s_k$  as a set of paths, each originating from the root of the light-tree (hub of  $s_k$ ) and terminating at one of its leaves (one of the members of  $s_k$ ). We refer to these paths as *root-to-leaf paths*. Note that the root of a light-tree (the hub for the corresponding session) is a decision variable and it is not known in advance.

The following constraints ensure that for each leaf of a light-tree there should be a root-to-leaf path originating from the root.

$$\sum_{n:P_{hn}=1} R_{hn}^{s_k,p,w} \geq LT_{s_k}^w - (1 - I_h^{s_k})Q \quad \forall s_k, p \in m_{s_k}, h \neq p, w \quad (3.13)$$

$$\sum_{n:P_{hn}=1} R_{hn}^{s_k,p,w} \leq LT_{s_k}^w + (1 - I_h^{s_k})Q \quad \forall s_k, p \in m_{s_k}, h \neq p, w \quad (3.14)$$

Note that when  $h$  is the hub node for session  $s_k$  ( $I_h^{s_k} = 1$ ), then  $\sum_{n:P_{hn}=1} R_{hn}^{s_k,p,w} = LT_{s_k}^w$ ; otherwise there will be no constraint ( $-Q \leq \sum_{n:P_{hn}=1} R_{hn}^{s_k,p,w} \leq Q$ ).

The following constraints ensure that for each leaf of a light-tree there should be a root-to-leaf path terminating at the leaf.

$$\sum_{m:P_{mp}=1} R_{mp}^{s_k,p,w} \geq LT_{s_k}^w - QI_p^{s_k} \quad \forall s_k, p \in m_{s_k}, w \quad (3.15)$$

$$\sum_{m:P_{mp}=1} R_{mp}^{s_k,p,w} \leq LT_{s_k}^w + QI_p^{s_k} \quad \forall s_k, p \in m_{s_k}, w \quad (3.16)$$

Note that when member  $p$  is not the hub node for session  $s_k$  ( $I_p^{s_k} = 0$ ), then  $\sum_{m:P_{mp}=1} R_{mp}^{s_k,p,w} = LT_{s_k}^w$ ; otherwise there will be no constraint ( $-Q \leq \sum_{m:P_{mp}=1} R_{mp}^{s_k,p,w} \leq Q$ ).

The following constraints ensure flow conservation at all intermediate nodes of a root-to-leaf path. They also guarantee that the same wavelength is used on all the fiber links traversed by the root-to-leaf path.

$$\sum_{m:P_{mx}=1} R_{mx}^{s_k,p,w} \leq \sum_{n:P_{xn}=1} R_{xn}^{s_k,p,w} \quad \forall s_k, p \in m_{s_k}, w, x \in V(x \neq p) \quad (3.17)$$

$$\sum_{m:P_{mx}=1} R_{mx}^{s_k,p,w} \geq \sum_{n:P_{xn}=1} R_{xn}^{s_k,p,w} - QI_x^{s_k} \quad \forall s_k, p \in m_{s_k}, w, x \in V(x \neq p) \quad (3.18)$$

Note that when  $x$  is not the hub node for session  $s_k$  ( $I_x^{s_k} = 0$ ), then flow conservation is maintained at  $x$  (i.e.,  $\sum_{m:P_{mx}=1} R_{mx}^{s_k,p,w} = \sum_{n:P_{xn}=1} R_{xn}^{s_k,p,w}$ ).

Constraints (3.13)-(3.18) ensure that for each light-tree for a session  $s_k$  there is a corresponding physical tree from the root (hub of  $s_k$ ) to the leaves (members or remaining members of  $s_k$ ), that uses the same wavelength all the fiber links it traverses.

The following constraints set the variable  $R_{mn}^{s_k,w}$  as the logical disjunction of  $R_{mn}^{s_k,p,w}$  variables for all values of  $p$ .

$$R_{mn}^{s_k,w} \geq \sum_{p \in m_{s_k}} R_{mn}^{s_k,p,w} / Q \quad \forall s_k, w, m, n : P_{mn} = 1 \quad (3.19)$$

$$R_{mn}^{s_k,w} \leq \sum_{p \in m_{s_k}} R_{mn}^{s_k,p,w} \quad \forall s_k, w, m, n : P_{mn} = 1 \quad (3.20)$$

$R_{mn}^{s_k,w}$  is set to 1 if at least one of the  $R_{mn}^{s_k,p,w}$  variables is set to 1 for any leaf  $p$ ; otherwise it is set to 0. The following constraint ensures that for any wavelength  $w$  on any fiber link  $mn$  no more than one lightpath or light-tree can be present.

$$\sum_{s_k} R_{mn}^{s_k,w} + \sum_i \sum_j F_{mn}^{ij,w} \leq 1 \quad \forall w, m, n : P_{mn} = 1 \quad (3.21)$$

Note, however, that root-to-leaf paths that belong to the same light-tree can use the same wavelength on the same fiber link.

*Hub Node Selection Constraints:*

The following constraint ensures that there is exactly one hub node for each session  $s_k$  chosen from the set of nodes in the network.

$$\sum_{h \in V} I_h^{s_k} = 1 \quad \forall s_k \quad (3.22)$$

The following constraints set the variable  $E_{s_l}^{s_k,h}$  as the logical conjunction of the variables  $I_h^{s_k}$  and  $I_h^{s_l}$ .

$$E_{s_l}^{s_k,h} \leq (I_h^{s_k} + I_h^{s_l})/2 \quad \forall s_k, s_l, h \quad (3.23)$$

$$E_{s_l}^{s_k,h} \geq I_h^{s_k} + I_h^{s_l} - 1 \quad \forall s_k, s_l, h \quad (3.24)$$

The following constraints set the variable  $E_{s_l}^{s_k}$  as the logical disjunction of  $E_{s_l}^{s_k,h}$  variables for all values of  $h$ .

$$E_{s_l}^{s_k} \geq \sum_h E_{s_l}^{s_k,h}/Q \quad \forall s_k, s_l \quad (3.25)$$

$$E_{s_l}^{s_k} \leq \sum_h E_{s_l}^{s_k,h} \quad \forall s_k, s_l \quad (3.26)$$

*Members-to-Hub Journey Constraints:*

In this set of constraints, we visualize the members-to-hub journey of a session as a set of streams, each originating from a member and terminating at the hub. Each of these streams, which we refer to as *member-to-hub streams*, may traverse multiple lightpaths from the member to the hub. It is to be noted that the destination of a member-to-hub stream is a decision



variable and it is not known in advance. The following constraint ensures that for each member-to-hub stream, there is a lightpath originating from the member unless it is the hub.

$$\sum_{i:i \neq p} D_{pi}^{s_k, p} = 1 - I_p^{s_k} \quad \forall s_k, p \in m_{s_k} \quad (3.27)$$

The following constraint ensures that for each member-to-hub stream, there is a lightpath terminating at the hub.

$$\sum_{i:i \neq h} D_{ih}^{s_k, p} \geq I_h^{s_k} \quad \forall s_k, p \in m_{s_k}, h \neq p \quad (3.28)$$

The following constraint ensures the continuity of a member-to-hub stream on multiple lightpaths.

$$\sum_{i:i \neq x} D_{ix}^{s_k, p} = \sum_{j:j \neq (x, p)} D_{xj}^{s_k, p} + I_x^{s_k} \quad \forall s_k, p \in m_{s_k}, x \in V(x \neq p) \quad (3.29)$$

The following constraint determines the total amount of traffic carried on lightpaths from node  $i$  to node  $j$  due to all members in session  $s_k$ .

$$X_{ij}^{s_k} = t_{s_k} \sum_{p \in m_{s_k}} D_{ij}^{s_k, p} \quad \forall s_k, i, j \quad (3.30)$$

The following constraint determines the total number of lightpaths needed between each pair of nodes in the network.

$$L_{ij} \geq \left( \sum_{s_k} X_{ij}^{s_k} \right) / g \quad \forall i, j \quad (3.31)$$

#### *Hub-to-Members Journey Constraints:*

In this set of constraints, we determine which light-trees are used in the hub-to-members journey of a session. The following constraint ensures that the hub-to-members journey of a session cannot be routed on a light-tree for another session unless the two sessions share the same hub node.

$$U_{s_l}^{s_k} \leq E_{s_l}^{s_k} \quad \forall s_k, s_l \quad (3.32)$$

The following constraint ensures that each member in a session is reached by at least one of the light-trees used in the hub-to-members journey of that session.

$$\sum_{s_l: p \in m_{s_l}} U_{s_l}^{s_k} \geq 1 \quad \forall s_k, p \in m_{s_k} \quad (3.33)$$

The following constraint determines the total amount of traffic carried on light-trees for session  $s_l$  due to members in session  $s_k$ .

$$T_{s_l}^{s_k} = U_{s_l}^{s_k} \times (N_{s_k} - 1) \times t_{s_k} \quad \forall s_k, s_l \quad (3.34)$$

The  $(N_{s_k} - 1)t_{s_k}$  traffic units represent the total amount of traffic after linearly combining the traffic units transmitted by members of session  $s_k$  at the hub node of session  $s_l$ . The following constraint determines the total number of light-trees needed for session  $s_k$ .

$$LT_{s_k} \geq (\sum_{s_l} T_{s_k}^{s_l})/g \quad \forall s_k \quad (3.35)$$

### 3.4 MILP Formulation for SAOWDM Networks

In a SAOWDM network, each member in a many-to-many session transmits its traffic directly to all other members in the same session using a light-tree, see Fig. 1.3 in Chapter 1. Each session  $s_k$  requires  $N_{s_k}$  light-trees while each light-tree requires  $N_{s_k}$  transceivers. Therefore, the total number of transceivers needed is:

$$R = \sum_{s_k} N_{s_k}^2$$

Note that the virtual topology is easily derived and no mathematical formulation is needed to derive it as in the previous networks. However, given the number of wavelengths per fiber  $W_{max}$ , finding a feasible routing and wavelength assignment for these light-trees is an NP-complete problem. This is a well studied problem in the literature and many mathematical formulations already exist. Therefore, in this report, we do not include a mathematical formulation for the problem, however, interested readers are referred to (41) for a complete MILP formulation.

### 3.5 Illustrative Numerical Example

In this section, we provide a detailed numerical example for the many-to-many traffic grooming problem in each of the four WDM networks. The example is conducted on the Abilene Research Network (42) (shown in Fig. 3.1) consisting of 10 nodes and 13 links (26 unidirectional fibers). The number of wavelengths per fiber,  $W_{max}$ , is set to six while the

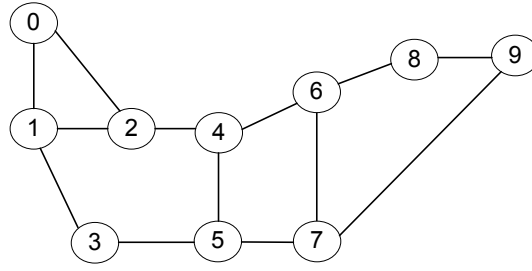


Figure 3.1 Abilene Research Network

Table 3.4 Sample traffic used in the example

Session	Members	Traffic Demand
$s_1$	$\{0,8\}$	3
$s_2$	$\{0,3,8\}$	16
$s_3$	$\{0,4,7,8,9\}$	8
$s_4$	$\{0,1,2\}$	13
$s_5$	$\{1,8\}$	11
$s_6$	$\{1,4\}$	5

grooming factor,  $g$ , is set to 16. A sample traffic consisting of six many-to-many sessions each with an arbitrary sub-wavelength traffic demand is shown in Table 3.4. Optimal solution for the many-to-many traffic grooming problem in each of the WDM networks is obtained by solving the corresponding MILP using the CPLEX solver (45).

Table 3.5 illustrates the many-to-many sessions provisioning in the NSOWDM network case. Totally, 50 lightpaths were established where some node pairs had two lightpaths between them ( $0 \rightarrow 1$ ,  $0 \rightarrow 2$ ,  $2 \rightarrow 0$ ,  $1 \rightarrow 2$ ,  $2 \rightarrow 1$ ,  $2 \rightarrow 4$ ,  $3 \rightarrow 1$ ,  $3 \rightarrow 5$ ,  $5 \rightarrow 4$ ,  $6 \rightarrow 7$ ,  $7 \rightarrow 9$ ,  $9 \rightarrow 8$ ) and some node pairs had three lightpaths between them ( $4 \rightarrow 6$ ,  $6 \rightarrow 4$ ,  $6 \rightarrow 8$ ,  $8 \rightarrow 6$ ) and some node pairs had four lightpaths between them ( $1 \rightarrow 0$ ,  $4 \rightarrow 2$ ), which required a total of 100 transceivers. The second column of the table shows all the lightpaths traversed to deliver traffic between members in the corresponding session. For example, the traffic from member 0 to member 8 in session  $s_1$  traverses lightpaths  $0 \rightarrow 1$ ,  $1 \rightarrow 2$ ,  $2 \rightarrow 4$ ,  $4 \rightarrow 6$  and  $6 \rightarrow 8$ , while the traffic from member 9 to member 0 in session  $s_3$  traverses lightpaths  $9 \rightarrow 8$ ,  $8 \rightarrow 6$ ,  $6 \rightarrow 4$ ,  $4 \rightarrow 2$  and  $2 \rightarrow 0$ . Traffic streams traversing the same lightpath are groomed together on that lightpath. For example, the traffic streams from members 0 and 4

in session  $s_3$  are groomed together on lightpaths  $4 \rightarrow 5$ ,  $5 \rightarrow 7$ ,  $7 \rightarrow 9$  and  $9 \rightarrow 8$ , while the traffic streams from members 8 and 4 in sessions  $s_5$  and  $s_6$ , respectively are groomed together on lightpaths  $4 \rightarrow 2$  and  $2 \rightarrow 1$ .

Table 3.5 Many-to-Many sessions provisioning in the NSOWDM network case

Session	Lightpaths Traversed
$s_1$	$0 \rightarrow 1$ , $1 \rightarrow 2$ , $2 \rightarrow 4$ , $4 \rightarrow 6$ , $6 \rightarrow 8$ , $8 \rightarrow 6$ , $6 \rightarrow 4$ , $4 \rightarrow 2$ , $2 \rightarrow 1$ , $1 \rightarrow 0$
$s_2$	$0 \rightarrow 1$ , $1 \rightarrow 3$ , $3 \rightarrow 5$ , $5 \rightarrow 4$ , $4 \rightarrow 6$ , $8 \rightarrow 6$ , $6 \rightarrow 7$ , $7 \rightarrow 5$ , $5 \rightarrow 3$ , $3 \rightarrow 1$ , $1 \rightarrow 0$
$s_3$	$0 \rightarrow 2$ , $2 \rightarrow 4$ , $4 \rightarrow 5$ , $5 \rightarrow 7$ , $7 \rightarrow 6$ , $7 \rightarrow 9$ , $9 \rightarrow 8$ , $8 \rightarrow 6$ , $6 \rightarrow 4$ , $6 \rightarrow 7$ , $4 \rightarrow 2$ , $2 \rightarrow 0$
$s_4$	$0 \rightarrow 1$ , $1 \rightarrow 2$ , $1 \rightarrow 0$ , $2 \rightarrow 1$ , $0 \rightarrow 2$
$s_5$	$1 \rightarrow 2$ , $2 \rightarrow 1$ , $2 \rightarrow 4$ , $4 \rightarrow 2$ , $4 \rightarrow 6$ , $6 \rightarrow 4$ , $6 \rightarrow 8$ , $8 \rightarrow 6$
$s_6$	$1 \rightarrow 2$ , $2 \rightarrow 4$ , $4 \rightarrow 2$ , $2 \rightarrow 1$

Table 3.6 illustrates the many-to-many sessions provisioning in the NSTWDM network case. Totally, 26 lightpaths were established where some node pairs had two lightpaths between them ( $8 \rightarrow 0$  and  $2 \rightarrow 1$ ), which required a total of 52 transceivers. The second column of the table shows all the lightpaths traversed to deliver traffic between members in the corresponding session. For example, the traffic from member 0 to member 8 in session  $s_1$  traverses lightpaths  $0 \rightarrow 2$  and  $2 \rightarrow 8$ , while the traffic from member 1 to member 8 in session  $s_5$  traverses lightpaths  $1 \rightarrow 4$ ,  $4 \rightarrow 2$  and  $2 \rightarrow 8$ . Traffic streams traversing the same lightpath are groomed together on that lightpath. For example, the traffic streams from members 0 and 4 in session  $s_3$  are groomed together on lightpath  $4 \rightarrow 9$ , while the traffic streams from members 0 and 1 in sessions  $s_1$  and  $s_5$ , respectively are groomed together on lightpath  $2 \rightarrow 8$ .

Table 3.7 illustrates the many-to-many sessions provisioning in the SHWDM network case. It shows the hub selected, the members-to-hub journey, and the hub-to-members journey for each session. Totally, nine lightpaths and eight light-trees were established, which required a total of 45 transceivers. For sessions  $s_2$ ,  $s_3$  and  $s_4$ , two light-trees were established, while a single light-tree was established for sessions  $s_1$  and  $s_6$ . Note that when there are only two members in a session and the hub is chosen to be one of them, then the light-tree for that session is simply a lightpath. For example, the light-tree for session  $s_1$  is simply a lightpath

Table 3.6 Many-to-Many sessions provisioning in the NSTWDM network case

Session	Lightpaths Traversed
$s_1$	$0 \rightarrow 2, 2 \rightarrow 8, 8 \rightarrow 1, 1 \rightarrow 0$
$s_2$	$0 \rightarrow 8, 8 \rightarrow 3, 3 \rightarrow 0, 3 \rightarrow 8, 8 \rightarrow 0, 0 \rightarrow 3$
$s_3$	$0 \rightarrow 4, 0 \rightarrow 7, 4 \rightarrow 8, 4 \rightarrow 9, 7 \rightarrow 0, 7 \rightarrow 4, 7 \rightarrow 9, 8 \rightarrow 0, 9 \rightarrow 7, 9 \rightarrow 8$
$s_4$	$0 \rightarrow 2, 1 \rightarrow 0, 1 \rightarrow 2, 2 \rightarrow 0, 2 \rightarrow 1$
$s_5$	$1 \rightarrow 4, 2 \rightarrow 8, 4 \rightarrow 2, 8 \rightarrow 1$
$s_6$	$1 \rightarrow 4, 2 \rightarrow 1, 4 \rightarrow 2$

Table 3.7 Many-to-Many sessions provisioning in the SHWDM network case

Session	Hub Node	Members-to-Hub Journey	Hub-to-Members Journey
$s_1$	8	$0 \rightarrow 8$	$8 \rightarrow \{0\}$
$s_2$	3	$0 \rightarrow 3, 8 \rightarrow 3$	$3 \rightarrow \{0, 8\}$
$s_3$	8	$0 \rightarrow 8, 4 \rightarrow 8, 7 \rightarrow 9, 9 \rightarrow 8$	$8 \rightarrow \{0, 4, 7, 9\}$
$s_4$	1	$0 \rightarrow 1, 2 \rightarrow 1$	$1 \rightarrow \{0, 2\}$
$s_5$	8	$1 \rightarrow 8$	$8 \rightarrow \{1, 4\}$
$s_6$	8	$1 \rightarrow 8, 4 \rightarrow 8$	$8 \rightarrow \{1, 4\}$

$8 \rightarrow 0$ . One can easily determine the lightpaths traversed to deliver the traffic from any member to the hub in the members-to-hub journey of a session by following the sequence of lightpaths between that member and the hub. For example, the traffic from member 7 to the hub 8 in session  $s_3$  traverses lightpaths  $7 \rightarrow 9$  and  $9 \rightarrow 8$ , while the traffic from member 0 to the hub 1 in session  $s_4$  traverses lightpath  $0 \rightarrow 1$ . The hub-to-members journey of a session either traverses light-trees for that session or light-trees for other sessions. For example, the hub-to-members journey of session  $s_3$  traverses the two light-trees for  $s_3$ , while the hub-to-members journey of session  $s_5$  traverses the light-tree for session  $s_6$ . Note that the light-tree for session  $s_6$  ( $8 \rightarrow \{1, 4\}$ ) grooms the linear combinations for both sessions  $s_5$  and  $s_6$ . Note also that the lightpath  $9 \rightarrow 8$  grooms the traffic from members 7 and 9 in session  $s_3$ , while the lightpath  $0 \rightarrow 8$  grooms the two traffic streams that originate from member 0 in sessions  $s_1$  and  $s_3$ , respectively.

Finally, Table 3.8 illustrates the many-to-many sessions provisioning in the SAOWDM network case. The second column of the table shows all the light-trees traversed by the

Table 3.8 Many-to-Many sessions provisioning in the SAOWDM network case

Session	Light-trees Traversed
$s_1$	$0 \rightarrow \{8\}, 8 \rightarrow \{0\}$
$s_2$	$0 \rightarrow \{3, 8\}, 3 \rightarrow \{0, 8\}, 8 \rightarrow \{0, 3\}$
$s_3$	$0 \rightarrow \{4, 7, 8, 9\}, 4 \rightarrow \{0, 7, 8, 9\}, 7 \rightarrow \{0, 4, 8, 9\}, 8 \rightarrow \{0, 4, 7, 9\}, 9 \rightarrow \{0, 4, 7, 8\}$
$s_4$	$0 \rightarrow \{1, 2\}, 1 \rightarrow \{0, 2\}, 2 \rightarrow \{0, 1\}$
$s_5$	$1 \rightarrow \{8\}, 8 \rightarrow \{1\}$
$s_6$	$1 \rightarrow \{4\}, 4 \rightarrow \{1\}$

corresponding session. Totally, 17 light-trees were established, which required a total of 55 transceivers.

In Chapter 4, we will use the MILPs introduced in this chapter to obtain the optimal solution for a number of experiments, where they will be compared to the solutions obtained by the proposed heuristics in that chapter.

### 3.6 Chapter Summary

In this chapter, we developed the optimal network design for each of the four WDM networks introduced in Chapter 1 for many-to-many traffic grooming. In each of the networks, we formulated a Mixed Integer Linear Programs (MILP). We also provided an illustrative numerical example from MILP solutions in each of the four WDM networks.

## CHAPTER 4. HEURISTIC SOLUTIONS

Although the MILPs in Chapter 3 guarantee an optimal solution for the many-to-many traffic grooming problem, they all have an exponential time complexity and can only be solved for relatively small sized instances of the problem. In this chapter, we introduce heuristic solutions for the many-to-many traffic grooming problem in each of the four WDM networks, which can be used to solve large sized instances of the problem.

Regarding notation, we use exactly the same notations provided in Tables 3.1, 3.2, and 3.3 in Chapter 3, and new symbols used in this chapter are defined when used. The rest of the chapter is organized as follows. In Section 4.1, we introduce *lightpath cycles* (a formal definition will be given later) as the optimal virtual topology for a number of special cases in NSOWDM and NSTWDM networks. In Section 4.2, based on observations from the optimal solution in each of the NSTWDM and the SHWDM networks, we restrict the solution space of the corresponding MILPs to obtain near-optimal solutions in a much shorter time. In Section 4.3, we introduce efficient near-optimal heuristic algorithms for the many-to-many traffic grooming problem in each of the four WDM networks. Finally, in Section 4.4, we summarize the chapter.

### 4.1 Lightpath Cycles

In this section, we derive the optimal virtual topology that minimizes the total number of transceivers required to provision many-to-many sessions in a number of special cases in NSOWDM and NSTWDM networks. First, we define  $H_{s_k}$  to be a lower bound on the number of incoming optical channels to a member in a session  $s_k$  in order to receive the traffic from the other  $N_{s_k} - 1$  members in the same session, which can be expressed as follows:

$$H_{s_k} = \lceil (N_{s_k} - 1)t_{s_k}/g \rceil$$

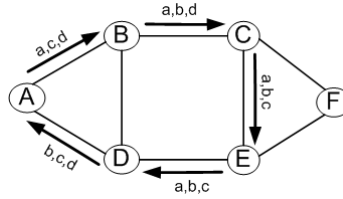


Figure 4.1 PPLC (which is also a MIN-PPLC) for a many-to-many session  $s_k$  with a set of members  $m_{s_k} = \{A, B, C, D\}$  each with one traffic unit denoted as  $a, b, c$  and  $d$ , respectively ( $g = 3, H_{s_k} = 1$ ).

#### 4.1.1 Lightpath Cycles in NSOWDM Networks

In a NSOWDM network, a lightpath can only span a single physical link and it may groom traffic from different sessions and traffic from different members within the same session.

**Definition 1.** Given a many-to-many session  $s_k$ :

1. A point-to-point lightpath-cycle (PPLC) for  $s_k$  is a (possibly non-simple) cycle of lightpaths that visits each member in  $m_{s_k}$  at least once given that a lightpath can only span a single physical link.
2. A minimum point-to-point lightpath-cycle (MIN-PPLC) for  $s_k$  is a PPLC for  $s_k$  with the minimum number of lightpaths traversed.

An example of a PPLC (which is also a MIN-PPLC) for a many-to-many session  $s_k$  with a set of members  $m_{s_k} = \{A, B, C, D\}$  is shown in Fig. 4.1. Note that, depending on the physical topology, it may not always be possible to find a simple cycle of lightpaths that visits each member in  $m_{s_k}$ . Therefore, a PPLC for  $s_k$  may be a non-simple cycle of lightpaths that visits a node more than once. A MIN-PPLC for a many-to-many session serves as an optimal virtual topology in a special case, as indicated by the following theorem:

**Theorem 1.** An optimal virtual topology that minimizes the total number of transceivers required to provision a single many-to-many session  $s_k$  in a NSOWDM network when  $H_{s_k} = 1$  consists of a MIN-PPLC for  $s_k$ .

*Proof.* First, we prove that any feasible virtual topology to provision  $s_k$  must contain a PPLC for  $s_k$ . Then, we prove that a PPLC for  $s_k$  by itself is feasible to provision  $s_k$  when  $H_{s_k} = 1$ .



Then, it follows that a MIN-PPLC for  $s_k$  is an optimal virtual topology when  $H_{s_k} = 1$  since it is a PPLC for  $s_k$  with the minimum number of lightpaths or transceivers.

Any feasible virtual topology to provision  $s_k$  must include a path from any member to any other member in  $m_{s_k}$ . This follows from the definition of the many-to-many traffic type where each member should transmit(receive) to(from) all the other members in the same session. Therefore, any order of the members in this virtual topology must form a PPLC for  $s_k$  that may visit a member multiple times.

To prove that a PPLC for  $s_k$  is feasible to provision  $s_k$  when  $H_{s_k} = 1$ , we must guarantee that in a PPLC for  $s_k$  each member in  $m_{s_k}$  receives the traffic from all the other  $N_{s_k} - 1$  members in the same session and that the capacity of a lightpath is not exceeded. Now, by letting each member in  $m_{s_k}$  to transmit its traffic in the PPLC until it reaches the member just before it in the cycle (see Fig. 4.1), we guarantee two things. First, exactly  $(N_{s_k} - 1)t_{s_k}$  traffic units are groomed between each pair of consecutive members in the PPLC and since  $H_{s_k} = 1$ , then a single lightpath is sufficient to groom this traffic. Second, each member in  $m_{s_k}$  receives the traffic from all the other  $N_{s_k} - 1$  members in the same session. Therefore, a PPLC for  $s_k$  is a feasible virtual topology.  $\square$

Note that a MIN-PPLC for  $s_k$  is the only optimal virtual topology to provision  $s_k$  when  $H_{s_k} = 1$  since, as we proved, any feasible virtual topology to provision  $s_k$  must include a PPLC for  $s_k$  and a MIN-PPLC for  $s_k$  is a PPLC with the minimum number of transceivers. Unfortunately, finding a MIN-PPLC for a many-to-many session  $s_k$  is a hard problem, as indicated by the following theorem:

**Theorem 2.** *Finding a MIN-PPLC for a many-to-many session  $s_k$  is NP-hard.*

*Proof.* We define the decision version of the PPLC problem as follows. Given a network represented by an undirected graph  $G(V, E)$ , a many-to-many session  $s_k$  with a set of members  $m_{s_k} \subseteq V$  and an integer  $c$ , the problem asks whether or not there is a PPLC for  $s_k$  in  $G$  that has at most  $c$  lightpaths. Now, consider any instance  $G'(V', E')$  of the undirected Hamiltonian cycle problem. We construct an instance of the decision version of the PPLC problem by

setting  $G = G'$ ,  $m_{s_k} = V'$  and  $c = |V'|$ . If the answer is "yes" to the decision version of the PPLC problem, then this PPLC must have exactly  $|V'|$  lightpaths since it needs to visit each member in  $m_{s_k} = V'$  at least once. This means that this PPLC must visit each node in  $V'$  exactly once, and therefore it will be a Hamiltonian cycle (hence, the answer is "yes" to the Hamiltonian cycle problem). On the other hand, if the answer is "yes" to the Hamiltonian cycle problem, then this Hamiltonian cycle is a PPLC of size  $|V'|$ , and hence the answer is "yes" to the decision version of the PPLC problem. This proves that the decision version of the PPLC problem is NP-complete, and hence the optimization version (MIN-PPLC) is NP-hard.  $\square$

This proves the hardness of the VTTR problem in a NSOWDM network for the simplest case of a single many-to-many session and  $H_{s_k} = 1$ . In the case where  $H_{s_k} \geq 2$ , the optimal virtual topology for a session  $s_k$  becomes harder to characterize and in the case of multiple many-to-many sessions, the problem becomes even harder due to the correlation between the sessions and the possibility of grooming traffic from different sessions on the same lightpath.

#### 4.1.2 Lightpath Cycles in NSTWDM Networks

In a NSTWDM network, a direct lightpath (that may span multiple physical links) can be established between any two nodes in the network. A lightpath may groom traffic from different sessions and traffic from different members within the same session.

**Definition 2.** *A transparent lightpath cycle (TLC) for a many-to-many session  $s_k$  is a simple cycle of  $N_{s_k}$  lightpaths that visits each member in  $m_{s_k}$  exactly once given that a lightpath may span multiple physical links.*

An example of a TLC for a many-to-many session  $s_k$  with a set of members  $m_{s_k} = \{A, B, C, D\}$  is shown in Fig. 4.2.(a). Note that there is always  $N_{s_k}$  lightpaths in the TLC for  $s_k$  regardless of the order of the members and regardless of the underlying physical topology (A TLC only describes a virtual topology). TLCs for a many-to-many session serve as an optimal virtual topology, as indicated by the following theorem:

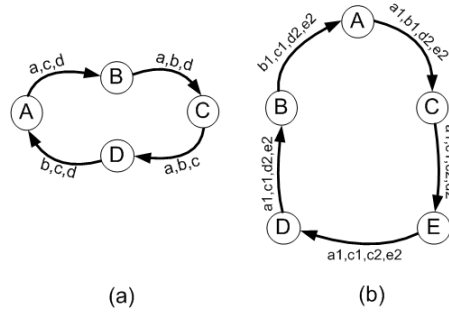


Figure 4.2 (a): TLC for a many-to-many session  $s_k$  where  $m_{s_k} = \{A, B, C, D\}$  each with one traffic unit denoted as  $a, b, c$  and  $d$ , respectively ( $g = 3, H_{s_k} = 1$ ), (b): TLC for many-to-many sessions  $s_1$  and  $s_2$  where  $m_{s_1} = \{A, B, C\}$  each with one traffic unit denoted as  $a1, b1, c1$  and  $m_{s_2} = \{C, D, E\}$  each with one traffic unit denoted as  $c2, d2, e2$  ( $g = 4$ ).

**Theorem 3.** *An optimal virtual topology that minimizes the total number of transceivers required to provision a single many-to-many session  $s_k$  in a NSTWDM network consists of  $H_{s_k}$  identically ordered TLCs for  $s_k$ .*

*Proof.* Any feasible virtual topology to provision  $s_k$  must at least have a total of  $N_{s_k} H_{s_k}$  lightpaths. This is due to the fact that each member in  $m_{s_k}$  must at least have  $H_{s_k}$  lightpaths incoming to receive its traffic. Note that  $H_{s_k}$  TLCs for  $s_k$  have exactly  $N_{s_k} H_{s_k}$  lightpaths. Therefore, if we prove it is a feasible virtual topology then it will also be an optimal one. Now, by letting each member to transmit its traffic in the  $H_{s_k}$  identically ordered TLCs until it reaches the member just before it in the TLCs (see Figure 4.2.(a)), we guarantee two things. First, exactly  $(N_{s_k} - 1)t_{s_k}$  traffic units are groomed between each pair of consecutive members in the TLCs and therefore  $H_{s_k}$  lightpaths are sufficient to groom this traffic. Second, each member in  $m_{s_k}$  receives the traffic from the other  $N_{s_k} - 1$  members in the same session. Therefore,  $H_{s_k}$  identically ordered TLCs is a feasible and an optimal virtual topology.  $\square$

Hence, for a single many-to-many session  $s_k$  in a NSTWDM network, the total number of transceivers required is:

$$R = 2H_{s_k} N_{s_k}$$

As we moved from NSOWDM networks to NSTWDM networks (toward more optical), the

optimal virtual topology for a single many-to-many session has changed from a hard problem (MIN-PPLC) to an easy problem (TLC). In the case of multiple many-to-many sessions, however, the problem is still hard due to the correlation between the sessions and the possibility of grooming traffic from different sessions on the same lightpath. However, in the following two special cases, the optimal virtual topology for multiple many-to-many sessions can be efficiently found. The first special case, which follows directly from Theorem 3, is when the member sets of the many-to-many sessions are pairwise disjoint. In this case, we have the following theorem:

**Theorem 4.** *An optimal virtual topology that minimizes the total number of transceivers required to provision a set of many-to-many sessions  $s_1, s_2, \dots, s_K$  when  $m_{s_k} \cap m_{s_l} = \phi$  for all  $1 \leq k \leq K$  and  $1 \leq l \leq K$  ( $k \neq l$ ) consists of  $\left\lceil \frac{(N_{s_m}-1)t_{s_m}}{g} \right\rceil$  identically ordered TLCs for  $s_m$ , for all  $1 \leq m \leq K$ .*

*Proof.* Since the member sets of the sessions are pairwise disjoint, then the argument made in the proof of Theorem 3 can now be made to each of the sessions independently.  $\square$

Hence, for this special case of multiple many-to-many sessions, the total number of transceivers required is:

$$R = 2 \sum_{s_k} H_{s_k} N_{s_k}$$

The second special case of multiple many-to-many sessions where the optimal virtual topology can be efficiently found is when  $\left\lceil \frac{\sum_{i=1}^K (N_{s_i}-1)t_{s_i}}{g} \right\rceil = 1$ , but first we make the following definition.

**Definition 3.** *A transparent lightpath cycle (TLC) for a set of many-to-many sessions  $s_1, s_2, \dots, s_K$  is a simple cycle of  $|\bigcup_{i=1}^K m_{s_i}|$  lightpaths that visits each member in the union set  $\bigcup_{i=1}^K m_{s_i}$  exactly once given that a lightpath may span multiple physical links.*

An example of a TLC for sessions  $s_1$  and  $s_2$  each with a set of members  $m_{s_1} = \{A, B, C\}$  and  $m_{s_2} = \{C, D, E\}$ , respectively is shown in Fig. 4.2.(b). Note that there is always  $|\bigcup_{i=1}^K m_{s_i}|$  lightpaths in the TLC for a set of sessions  $s_1, s_2, \dots, s_K$  regardless of the order of the members and regardless of the underlying physical topology (A TLC for a set of sessions only describes

a virtual topology). A TLC for a set of many-to-many sessions serves as an optimal virtual topology in a special case, as indicated by the following theorem:

**Theorem 5.** *An optimal virtual topology that minimizes the total number of transceivers required to provision a set of many-to-many sessions  $s_1, s_2, \dots, s_K$  in a NSTWDM network when  $\lceil (\sum_{i=1}^K (N_{s_i} - 1)t_{s_i})/g \rceil = 1$  consists of a TLC for  $s_1, s_2, \dots, s_K$ .*

*Proof.* Any feasible virtual topology to provision the set of sessions  $s_1, s_2, \dots, s_K$  must at least have a total of  $|\bigcup_{i=1}^K m_{s_i}|$  lightpaths. This is due to the fact that each member in  $\bigcup_{i=1}^K m_{s_i}$  must at least have one lightpath incoming to receive its traffic. Note that a TLC for  $s_1, s_2, \dots, s_K$  has exactly  $|\bigcup_{i=1}^K m_{s_i}|$  lightpaths. Therefore, if we prove it is a feasible virtual topology then it will also be an optimal one. Now, by letting each member in  $\bigcup_{i=1}^K m_{s_i}$  to transmit its traffic in the TLC until it reaches the last member interested in receiving this traffic (see Figure 4.2.(b)), we guarantee two things. First, exactly  $\sum_{i=1}^K (N_{s_i} - 1)t_{s_i}$  traffic units are groomed between each pair of consecutive members in the TLC and since  $\lceil (\sum_{i=1}^K (N_{s_i} - 1)t_{s_i})/g \rceil = 1$ , then a single lightpath is sufficient to groom this traffic. Second, each member in  $\bigcup_{i=1}^K m_{s_i}$  receives the traffic from all the other  $N_{s_k} - 1$  members in all sessions  $s_k$  where this member appears. Therefore, a TLC for  $s_1, s_2, \dots, s_K$  is a feasible and an optimal virtual topology.  $\square$

Hence, for this special case of multiple many-to-many sessions, the total number of transceivers required is:

$$R = 2 \left| \bigcup_{i=1}^K m_{s_i} \right|$$

The above theorem is quite useful when traffic demands of user sessions are much less than the capacity of an optical channel. The general case of the many-to-many traffic grooming problem remains a hard problem due to the correlation between the sessions and the possibility of grooming traffic from different sessions on the same lightpath.

In Section 4.3, lightpath cycles (point-to-point and transparent) will be used as the bases for designing efficient near-optimal heuristic algorithms for the many-to-many traffic grooming problem in NSOWDM and NSTWDM networks.

## 4.2 Restricting MILPs

In this section, we develop heuristic solutions for the many-to-many traffic grooming problem in NSTWDM and SHWDM networks by restricting the solution space of the corresponding MILPs introduced in Chapter 3. These MILP restrictions are based on observations made from the optimal solution. Although the restricted MILPs still have an exponential time complexity and they result in a sub-optimal solution, they will reduce the running time significantly while not sacrificing the quality of the solution that much, as we shall see.

### 4.2.1 Restricting the NSTWDM networks MILP

After careful examination of the MILP results for small and medium sized instances of the problem, we have made an observation on how many-to-many sessions tend to be provisioned in NSTWDM networks.

**Observation 1.** *Many-to-many sessions in NSTWDM networks tend to be provisioned through TLCs, where each session  $s_k$  is provisioned through  $H_{s_k}$  identically ordered TLCs for  $s_k$ .*

Since a lightpath may groom traffic from different sessions and not just traffic from different members within the same session, TLCs of different sessions may share lightpaths. This introduces a correlation between TLCs where the order of the members becomes significant and must be taken into account. Fig. 4.3.(a) clarifies this point by illustrating the provisioning of two many-to-many sessions  $s_1$  and  $s_2$  each with a set of members  $m_{s_1} = \{A, B, C\}$  and  $m_{s_2} = \{B, C, D\}$ , respectively through TLCs. Note that the TLC for session  $s_1$  ( $A-B-C-A$ ) and the TLC for session  $s_2$  ( $B-C-D-B$ ) share the lightpath  $B \rightarrow C$ . Precisely, the lightpath  $B \rightarrow C$  grooms the two traffic units  $b_1, a$  belonging to session  $s_1$  and the two traffic units  $b_2, d$  belonging to session  $s_2$ . Note that the order of the members in the TLCs is significant. For example, if order of the members in the TLC for  $s_2$  is  $B-D-C-B$  instead of  $B-C-D-B$ , then the two TLCs for  $s_1$  and  $s_2$  will not share a lightpath and we would require six lightpaths instead of five (see Fig. 4.3.(b)).

The above observation is the basis for designing our heuristic for the many-to-many traffic

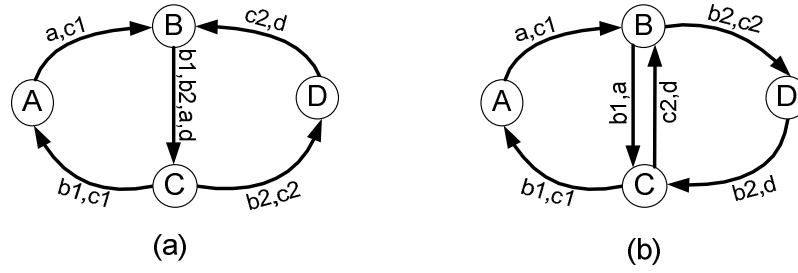


Figure 4.3 (a): Provisioning of sessions  $s_1$  and  $s_2$ , where  $m_{s_1} = \{A, B, C\}$  each with one traffic unit denoted as  $a, b_1, c_1$ , and  $m_{s_2} = \{B, C, D\}$  each with one traffic unit denoted as  $b_2, c_2, d$  ( $g = 4$ ). The order of the members in the TLCs for  $s_1$  and  $s_2$  is  $A - B - C - A$  and  $B - C - D - B$ , respectively. (b): same as part (a) except that the order of the members in the TLCs for  $s_1$  and  $s_2$  is  $A - B - C - A$  and  $B - D - C - B$ , respectively.

grooming problem in NSTWDM networks. In the heuristic, we assume that every many-to-many session  $s_k$  is provisioned through  $H_{s_k}$  identically ordered TLCs for  $s_k$ . Although this assumption may not result in an optimal solution, assuming it always holds, as we shall see, will lead to near optimal solutions. Based on this assumption, we just need to determine the order of the members in the sessions' TLCs and then route the traffic on the TLCs as described before (see Fig. 4.2.(a)). Note that, between each pair of nodes  $i$  and  $j$ , the heuristic grooms the  $\sum_{s_k} (N_{s_k} - 1)t_{s_k}$  traffic units for all sessions  $s_k$  where  $i, j \in m_{s_k}$  and member  $j$  follows member  $i$  immediately in the session's TLCs.

Applying the above observation to the MILP means a significant simplification, since we do not need to consider the sessions' traffic routing once we determine the order of the members in the sessions' TLCs. Therefore, we no longer require the  $Z_{ij}^{s_k, p, q}$  and  $Y_{ij}^{s_k, p}$  variables, however, we require the following two new variables.

- $C_{p,q}^{s_k}$  binary number equals to 1 if member  $p \in m_{s_k}$  is followed immediately by member  $q \in m_{s_k}$  in the TLCs for session  $s_k$ ; otherwise it is set to 0.
- $u_p^{s_k}$  an arbitrary real number.

The lightpath level constraints remain unchanged, while the session level constraints are replaced by the following set of constraints.

Table 4.1 Many-to-Many sessions provisioning in the NSTWDM network case using the heuristic MILP for the example in Section 3.5 in Chapter 3

Session	Lightpaths Traversed
$s_1$	$0 \rightarrow 8, 8 \rightarrow 0$
$s_2$	$0 \rightarrow 3, 3 \rightarrow 8, 8 \rightarrow 0$
$s_3$	$0 \rightarrow 9, 9 \rightarrow 8, 8 \rightarrow 4, 4 \rightarrow 7, 7 \rightarrow 0$
$s_4$	$0 \rightarrow 1, 1 \rightarrow 2, 2 \rightarrow 0$
$s_5$	$1 \rightarrow 8, 8 \rightarrow 1$
$s_6$	$1 \rightarrow 4, 4 \rightarrow 1$

*Session Level Constraints:*

$$\sum_{q \neq p} C_{p,q}^{s_k} = \sum_{q \neq p} C_{q,p}^{s_k} = 1 \quad \forall s_k, p \in m_{s_k} \quad (4.1)$$

$$u_p^{s_k} - u_q^{s_k} + N_{s_k} C_{p,q}^{s_k} \leq N_{s_k} - 1 \quad \forall s_k, p \in (m_{s_k} - m_{s_k}[0]), q \in m_{s_k} (q \neq p) \quad (4.2)$$

$$L_{ij} \geq \sum_{s_k} (N_{s_k} - 1) t_{s_k} C_{i,j}^{s_k} / g \quad \forall i, j \quad (4.3)$$

Constraint (4.1) determines the order of the members in each session's TLCs, while constraint (4.2) ensures that a TLC for session  $s_k$  must include all members in  $m_{s_k}$  ( $m_{s_k}[0]$  represents the first member in  $m_{s_k}$ ). In other words, constraint (4.2) eliminates all sub-TLCs (TLCs that visit only a subset of the members). Constraint (4.3) computes the total number of lightpaths needed between each pair of nodes in the network. It calculates the total traffic from node  $i$  to node  $j$  as the aggregate traffic from all sessions who have member  $i$  followed immediately by member  $j$  in their TLCs.

Although this heuristic approach remains an MILP, it will be shown that it is a practical one that leads to near optimal solutions of large networks in a reasonable time. Solving the illustrative numerical example in Section 3.5 in Chapter 3 using this heuristic MILP, we obtain the many-to-many sessions provisioning shown in Table 4.1. Totally, 28 lightpaths were established where some node pairs had two lightpaths between them ( $0 \rightarrow 1, 2 \rightarrow 0, 0 \rightarrow 3, 7 \rightarrow 0, 0 \rightarrow 9, 1 \rightarrow 2, 3 \rightarrow 8, 4 \rightarrow 7, 8 \rightarrow 4, 9 \rightarrow 8$ ) and some node pairs had three lightpaths between them ( $8 \rightarrow 0$ ), which required a total of 56 transceivers compared to 52 transceivers in the optimal solution in Section 3.5 in Chapter 3. Note that sessions  $s_1, s_5$  and  $s_6$  are provisioned by a single TLC, while sessions  $s_2, s_3$  and  $s_4$  are provisioned by two TLCs.



The solution from the heuristic MILP was obtained in 2.5 seconds, while the optimal solution in Section 3.5 in Chapter 3 was obtained in almost one hour and six minutes. This is a significant reduction in the running time, while still obtaining near optimal solutions (7.7% more than the optimal solution).

#### 4.2.2 Restricting the SHWDM networks MILP

After careful examination of the MILP results for small and medium sized instances of the problem, we have made observations on how many-to-many sessions tend to be provisioned in SHWDM networks.

**Observation 2.** *The hub for a many-to-many session is usually selected from its set of members.*

**Observation 3.** *A member-to-hub stream in the members-to-hub journey of a many-to-many session usually traverses a single direct lightpath from the member to the hub.*

**Observation 4.** *Light-trees usually do not groom traffic from different sessions; they only groom the linear combinations for the corresponding session.*

These observations are the bases for designing our heuristic for the many-to-many traffic grooming problem in SHWDM networks. The heuristic is based on the assumption that these observations always hold. Although this assumption may not result in an optimal solution, assuming it always holds, as we shall see, will lead to near optimal solutions. Applying the above observations to the MILP means a significant simplification.

*Number of Transceivers Constraints:*

Since the hub of a many-to-many session  $s_k$  can only be selected from its set of members  $m_{s_k}$ , a light-tree for  $s_k$  places one transceiver at each member in  $m_{s_k}$  and does not place a transceiver at any other node. Therefore, we no longer require the non-linear variable  $A_h^{s_k}$ , and the number of transceivers constraints are replaced by the following constraint.

$$R_i \geq \sum_{j:j \neq i} (L_{ij} + L_{ji}) + \sum_{s_k} LT_{s_k} B_i^{s_k} \quad \forall i \quad (4.4)$$

The lightpath/light-tree level constraints remain unchanged.

*Hub Node Selection Constraints:*

Since the hub of a many-to-many session  $s_k$  can only be selected from its set of members  $m_{s_k}$ , we no longer require the variable  $I_h^{s_k}$  to be defined for all  $h \in V$ , rather it is defined only for  $h \in m_{s_k}$ . Also, since light-trees do not groom traffic from different sessions, we no longer require the  $E_{s_l}^{s_k, h}$  and  $E_{s_l}^{s_k}$  variables. Accordingly, the hub selection constraints are replaced by the following constraint, which ensures that there is exactly one hub node for each session chosen from its set of members.

$$\sum_{h \in m_{s_k}} I_h^{s_k} = 1 \quad \forall s_k \quad (4.5)$$

*Members-to-Hub Journey Constraints:*

Assuming that a member-to-hub stream traverses a single direct lightpath from the member to the hub, we no longer require the  $D_{ij}^{s_k, p}$  variables. Accordingly, the members-to-hub journey constraints are replaced by the following constraint.

$$L_{ij} \geq \left( \sum_{s_k} t_{s_k} I_j^{s_k} B_i^{s_k} \right) / g \quad \forall i, j \quad (i \neq j) \quad (4.6)$$

The above constraint ensures that if node  $i \in m_{s_k}$  and node  $j$  is the hub for  $s_k$ , then lightpaths from  $i$  to  $j$  carry the  $t_{s_k}$  traffic units that originate from member  $i$ .

*Hub-to-Members Journey Constraints:*

Since light-trees do not groom traffic from different sessions and they only groom the linear combinations for the corresponding session, we no longer require the  $U_{s_l}^{s_k}$  and  $T_{s_l}^{s_k}$  variables. Accordingly, the hub-to-members journey constraints are replaced by the following constraint.

$$LT_{s_k} = H_{s_k} \quad \forall s_k \quad (4.7)$$

Although this heuristic approach remains an MILP, it will be shown that it is a practical one that leads to near optimal solutions of large networks in a reasonable time. Solving the illustrative numerical example in Section 3.5 in Chapter 3 using this heuristic MILP, we obtain the many-to-many sessions provisioning shown in Table 4.2. It shows the hub selected, the members-to-hub journey, and the hub-to-members journey for each session. Totally, 10

Table 4.2 Many-to-Many sessions provisioning in the SHWDM network case using the heuristic MILP for the example in Section 3.5 in Chapter 3

Session	Hub node	members-to-hub journey	hub-to-members journey
$s_1$	8	$0 \rightarrow 8$	$8 \rightarrow \{0\}$
$s_2$	3	$0 \rightarrow 3, 8 \rightarrow 3$	$3 \rightarrow \{0, 8\}$
$s_3$	8	$0 \rightarrow 8, 4 \rightarrow 8, 7 \rightarrow 8, 9 \rightarrow 8$	$8 \rightarrow \{0, 4, 7, 9\}$
$s_4$	0	$1 \rightarrow 0, 2 \rightarrow 0$	$0 \rightarrow \{1, 2\}$
$s_5$	1	$8 \rightarrow 1$	$1 \rightarrow \{8\}$
$s_6$	1	$4 \rightarrow 1$	$1 \rightarrow \{4\}$

lightpaths and 9 light-trees were established, which required a total of 48 transceivers compared to 45 transceivers in the optimal solution in Section 3.5 in Chapter 3. For sessions  $s_2$ ,  $s_3$  and  $s_4$ , two light-trees were established, while a single light-tree was established for each of sessions  $s_1$ ,  $s_5$  and  $s_6$ . Note that the light-trees for sessions  $s_1$ ,  $s_5$  and  $s_6$  were simply the lightpaths  $8 \rightarrow 0$ ,  $1 \rightarrow 8$  and  $1 \rightarrow 4$ , respectively.

The solution from the heuristic MILP was obtained in 13 seconds, while the optimal solution in Section 3.5 in Chapter 3 was obtained in almost two hours and one minute. This is a significant reduction in the running time, while still obtaining near optimal solutions (6.7% more than the optimal solution).

The advantage of using network coding in this heuristic is the reduction of downstream traffic for each session  $s_k$  from  $N_{s_k}t_{s_k}$  to  $(N_{s_k} - 1)t_{s_k}$  traffic units. The total number of transceivers saved due to the use of network coding ( $R_{saved}$ ) is equal to the total number of light-trees saved for each session  $s_k$  ( $\lceil N_{s_k}t_{s_k}/g \rceil - \lceil (N_{s_k} - 1)t_{s_k}/g \rceil$ ) times the total number of transceivers per light-tree for that session ( $N_{s_k}$ ), which is indicated by the following equation:

$$R_{saved} = \sum_{s_k} N_{s_k} (\lceil N_{s_k}t_{s_k}/g \rceil - \lceil (N_{s_k} - 1)t_{s_k}/g \rceil) \quad (4.8)$$

It is to be noted that this equation may not hold for the optimal approach where light-trees may groom traffic from different sessions and the hub can be any node in the network (not just the members). The total number of transceivers saved in that case can only be determined by solving the optimal MILP with network coding (downstream traffic is  $(N_{s_k} - 1)t_{s_k}$  traffic units) and without network coding (downstream traffic is  $N_{s_k}t_{s_k}$  traffic units) and then taking

the difference.

### 4.2.3 Complexity Analysis

The complexity of the optimal MILP for NSTWDM networks in terms of the number of integer variables is  $O(KN^4 + W|E|N^2)$ , and in terms of the number of constraints is  $O((K + W)N^3)$ . The complexity of the optimal MILP for SHWDM networks in terms of the number of integer variables is  $O(KN^3 + KW|E|N + K^2N + W|E|N^2)$ , and in terms of the number of constraints is  $O(WN^3 + KWN^2 + K^2N)$ .

The complexity of the heuristic (or restricted) MILP for NSTWDM networks in terms of the number of integer variables is  $O(KN^2 + W|E|N^2)$ , and in terms of the number of constraints is  $O(WN^3 + KN^2)$ . The complexity of the heuristic (or restricted) MILP for SHWDM networks in terms of the number of integer variables is  $O(KW|E|N + W|E|N^2)$ , and in terms of the number of constraints is  $O(WN^3 + KWN^2)$ .

### 4.2.4 Numerical Results

To verify the performance of our proposed heuristics, we conduct a number of experiments on small, medium and large sized networks. Five experiments are conducted on a small sized network (the 6-node network shown in Fig. 4.4.(a)). The number of sessions in each experiment is randomly selected between [2,4]. The number of members in a session is randomly selected between [2,5], while a member in a session is randomly selected between [0,5]. Another five experiments are conducted on a medium sized network (the Abilene network shown in Fig. 3.1 in Chapter 3). The number of sessions in each experiment is randomly selected between [4,6]. The number of members in a session is randomly selected between [2,5], while a member in a session is randomly selected between [0,9]. Another five experiments are conducted on a large sized network (the NSF network shown in Fig. 4.4.(b)). The number of sessions in each experiment is randomly selected between [6,8]. The number of members in a session is randomly selected between [2,5], while a member in a session is randomly selected between [0,13]. Finally, traffic demand of members in a session, in all the 15 experiments, is randomly

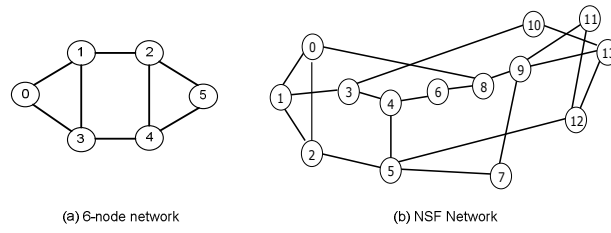


Figure 4.4 Networks used in the results

Table 4.3 Average running time and average number of transceivers for the 5 experiments conducted on each of the 6-node, Abilene and NSF networks in the NSTWDM network case

Network	MILP	Avg. Run Time	Avg. # of TRs
6-node	Optimal MILP	15 hours	46.2
	Heuristic MILP	6 seconds	49.1
Abilene	Optimal MILP	108 Hours	62.4
	Heuristic MILP	3 Minutes	66
NSF	Optimal MILP	>150 hours	No Solution
	Heuristic MILP	1 Hour	88.8

selected between  $[1,16]$  ( $g = 16$ ).

For both NSTWDM and SHWDM network cases, we solve each of the 15 experiments using the optimal MILP and the heuristic MILP. Tables 4.3 and 4.4 present the results by showing the average running time and the average number of transceivers for the five experiments on each of the three topologies in NSTWDM and SHWDM network cases, respectively.

We can see from Tables 4.3 and 4.4 that solutions from the heuristics on the 6-node network are significantly close to their corresponding optimal solutions. For example, in the NSTWDM network case, they are, on average, 6.2% of their corresponding optimal solutions, while in the SHWDM network case they are, on average, 5.5% of their corresponding optimal solutions.

In some experiments on the Abilene network, we could not obtain the optimal solution after 150 hours of running time at which we have terminated the CPLEX program and recorded the best feasible solution. The largest gap we have encountered between the best feasible solution and the best lower bound found by CPLEX was only 3%. This means that the best feasible solutions obtained were very close to their corresponding optimal solutions. We can

Table 4.4 Average running time and average number of transceivers for the 5 experiments conducted on each of the 6-node, Abilene and NSF networks in the SHWDM network case

Network	MILP	Avg. Run Time	Avg. # of TRs
6-node	Optimal MILP	6 hours	41
	Heuristic MILP	33 seconds	43.2
Abilene	Optimal MILP	57 Hours	54.4
	Heuristic MILP	4 Minutes	57
NSF	Optimal MILP	>150 hours	No Solution
	Heuristic MILP	2 Hours	78.6

see from Tables 4.3 and 4.4 that solutions from the heuristics on the Abilene network are significantly close to their corresponding optimal (or best feasible) solutions. For example, in the NSTWDM network case, they are, on average, 5.8% of their corresponding optimal (or best feasible) solutions, while in the SHWDM network case they are, on average, 4.7% of their corresponding optimal (or best feasible) solutions.

In the NSF experiments, the CPLEX program did not return a feasible solution for any of the five experiments (using the optimal MILP) after 150 hours of running time at which we have terminated the program. On the other hand, the heuristic MILPs for both NSTWDM and SHWDM network cases were able to return solutions in a reasonable time.

Next, NSTWDM and SHWDM networks will be compared in terms of the number of transceiver needed ( $R$ ). We will show when each of these two networks is a more cost-effective choice (in terms of  $R$ ) for many-to-many traffic grooming. Since the grooming capabilities of the two networks are varied, their performance will be dependent on traffic granularities of sessions in the network. Therefore, we should compare them for different traffic granularities.

1) *Uniform Traffic*: We assume a static uniform traffic with all sessions in an experiment having the same traffic demand  $t$  (i.e.,  $t_{s_1} = t_{s_2} = \dots = t_{s_K} = t$ ), where  $1 \leq t \leq g$ . Fifteen randomly generated experiments are conducted on the Abilene network shown in Fig. 3.1 in Chapter 3. The number of sessions in each experiment is randomly selected between [2,6]. The size of each session is randomly selected between [2,5], while a member in a session is randomly selected between [0,9]. Based on the uniform traffic assumption, each of the fifteen experiments

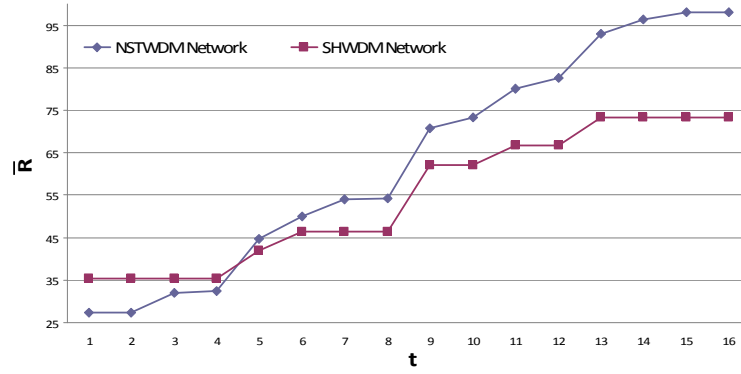


Figure 4.5 Values of  $\bar{R}$  for  $t = 1, 2, \dots, g$  on the Abilene network ( $g = 16$ )

is conducted for each value of  $t = 1, 2, \dots, g$  ( $g = 16$ ) on both NSTWDM and SHWDM networks using the corresponding heuristic MILP. We define  $\bar{R}$  to be the average value of all  $R$  values obtained from the fifteen experiments at a particular value of  $t$  on a certain network. The resulting values of  $\bar{R}$  are shown in Fig. 4.5.

From Fig. 4.5, we draw the following conclusions:

- NSTWDM networks are more cost-effective when traffic granularities of sessions are relatively low ( $t \leq g/4$ ). The intuition behind this is that lightpaths are more efficient than light-trees in grooming and packing low granularity traffic. This is a result of the point-to-point nature of a lightpath where it is possible to route many sessions or members with sub-wavelength granularities through it. Note that, contrary to a lightpath, it is not easy to route many sessions with sub-wavelength granularities through a point-to-multipoint channel (i.e., a light-tree).
- SHWDM networks are more cost-effective for almost three quarters of the traffic granularities spectrum ( $t > g/4$ ). The intuition behind this is that when traffic granularities of sessions are relatively high, inter-session grooming is rarely performed and in that case light-trees are more cost-effective than lightpaths. For example, a light-tree from a source to a set of destinations requires fewer transceivers than a set of lightpaths each from the source to one of the destinations. Also, the use of network coding in SHWDM networks has a direct impact on reducing the number of light-trees needed, and hence

Table 4.5 Number of transceivers (R) comparison on the Abilene network with non-uniform traffic

Exp #	1	2	3	4	5	6
$\bar{t}$	2.1	3.6	7.7	9.5	11.1	13.8
NSTWDM Networks	28	38	48	56	58	70
SHWDM Networks	35	40	45	50	50	55

the number of transceivers.

2) *Non-Uniform Traffic*: Although the above conclusions are drawn from the uniform traffic assumption, we will now show that they remain valid even when traffic demands of user sessions are non-uniform. In this case, however, we define  $\bar{t}$  to be the average amount of traffic demanded by a member in an experiment, which is expressed by the following equation:

$$\bar{t} = \frac{\sum_{s_k} N_{s_k} t_{s_k}}{\sum_{s_k} N_{s_k}}$$

We claim that the above conclusions remain valid for different values of  $\bar{t}$ . To verify this, we randomly generate six experiments on the Abilene network with the same parameters as the fifteen experiments generated earlier, however, the traffic demand of members in a session is now randomly selected between [1,16] (non-uniform traffic). Each of the experiments is conducted in both NSTWDM and SHWDM networks using the corresponding heuristic MILP. The resulting values of  $R$  are shown in Table 4.5. We can see from the table that NSTWDM networks are more cost-effective when  $\bar{t} \leq g/4$  (Exps. 1 and 2), while SHWDM networks are more cost-effective when  $\bar{t} > g/4$  (Exps. 3, 4, 5 and 6).

To illustrate the advantage of network coding in reducing the number of transceivers in SHWDM networks, we compute the values of  $R_{saved}$  for each of the fifteen uniform traffic experiments at each value of  $t = 1, 2, 3, \dots, 16$  using Eq. (4.8). We define  $\overline{R_{saved}}$  to be the average value of all  $R_{saved}$  values obtained from the fifteen experiments at a particular value of  $t$ . Tables 4.6 and 4.7 show the corresponding values of  $\overline{R_{saved}}$  and the corresponding percentage savings due to the use of network coding ( $\overline{R_{saved}}/\overline{R}$ ) for  $t = \{1, 2, 3, 4, 5, 6, 7, 8\}$  and for  $t = \{9, 10, 11, 12, 13, 14, 15, 16\}$ , respectively.



Table 4.6 Values of  $\overline{R_{saved}}$  and  $(\overline{R_{saved}}/\overline{R})$  for  $t=1,2,3,4,5,6,7,8$  ( $g = 16$ ) on the Abilene network

$t$	1	2	3	4	5	6	7	8
$\overline{R_{saved}}$	0	0	0	2.7	1.6	5.2	7.9	7.9
$\overline{R_{saved}}/\overline{R}$	0%	0%	0%	7.6%	3.8%	11.2%	17%	17%

Table 4.7 Values of  $\overline{R_{saved}}$  and  $(\overline{R_{saved}}/\overline{R})$  for  $t=9,10,11,12,13,14,15,16$  ( $g = 16$ ) on the Abilene network

$t$	9	10	11	12	13	14	15	16
$\overline{R_{saved}}$	3.7	6.4	10	10	11.6	11.6	11.6	11.6
$\overline{R_{saved}}/\overline{R}$	6%	10.3%	15%	15%	15.8%	15.8%	15.8%	15.8%

### 4.3 Heuristic Algorithms

In this section, we introduce heuristic algorithms for the many-to-many traffic grooming problem in each of the four WDM networks. Our solution approach is to first separate the many-to-many traffic grooming problem into the VTTR and the RWA problems and then solve each problem independently (VTTR then RWA). The objective of the VTTR problem is to minimize the total number of transceivers  $R$ , while the objective of the RWA problem is to minimize the total number of wavelengths used  $W$ . This separation approach simplifies the overall problem and allows us to obtain efficient solutions. First, we introduce heuristic algorithms for the VTTR problem in each of the WDM networks (except the SAOWDM network where the optimal virtual topology is straightforward), and then we address the RWA problem.

#### 4.3.1 Heuristic Algorithm for NSOWDM Networks

After careful examination of the MILP results for small sized instances of the problem and for multiple sessions, we have noticed that many-to-many sessions in NSOWDM networks tend to be provisioned through PPLCs where, for each session  $s_k$ ,  $(N_{s_k} - 1)t_{s_k}$  traffic units are groomed between each pair of consecutive members in the PPLCs. Since a lightpath may groom traffic from different sessions and not just traffic from different members within the same

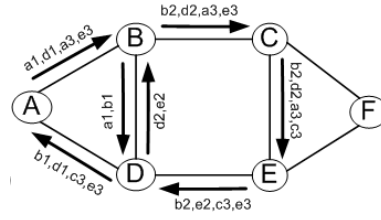


Figure 4.6 Optimal provisioning of many-to-many sessions  $s_1$ ,  $s_2$  and  $s_3$  where  $m_{s_1} = \{A, B, D\}$  each with one traffic unit denoted as  $a1, b1, d1$ , and  $m_{s_2} = \{B, D, E\}$  each with one traffic unit denoted as  $b2, d2, e2$ , and  $m_{s_3} = \{A, C, E\}$  each with one traffic unit denoted as  $a3, c3, e3$  in a NSOWDM network case ( $g = 4$ ).

session, PPLCs of different sessions are correlated and may share lightpaths. Fig. 4.6 clarifies this point by illustrating the optimal provisioning of three many-to-many sessions  $s_1$ ,  $s_2$  and  $s_3$  each with a set of members  $m_{s_1} = \{A, B, D\}$ ,  $m_{s_2} = \{B, D, E\}$  and  $m_{s_3} = \{A, C, E\}$ , respectively in a NSOWDM network case ( $g = 4$ ). Note that the PPLC for  $s_1$  ( $A - B - D - A$ ) and the PPLC for  $s_3$  ( $A - B - C - E - D - A$ ) share lightpaths  $A \rightarrow B$  and  $D \rightarrow A$ , while the PPLC for  $s_2$  ( $B - C - E - D - B$ ) and the PPLC for  $s_3$  share lightpaths  $B \rightarrow C$ ,  $C \rightarrow E$  and  $E \rightarrow D$ . For example, the lightpath  $D \rightarrow A$  grooms the two traffic units  $b1, d1$  belonging to session  $s_1$  and the two traffic units  $c3, e3$  belonging to session  $s_3$ , while the lightpath  $C \rightarrow E$  grooms the two traffic units  $b2, d2$  belonging to session  $s_2$  and the two traffic units  $a3, e3$  belonging to session  $s_3$ .

The heuristic we propose for the VTTR problem in NSOWDM networks is based on the observation that many-to-many sessions tend to be provisioned through PPLCs. The heuristic also takes the correlation (sharing of lightpaths) between PPLCs of different sessions into account. As a first step, we need to find an efficient way of finding a PPLC for a session  $s_k$  with a number of lightpaths close to that of a MIN-PPLC for that session. Finding a PPLC for a session  $s_k$  in  $G$  requires us to determine two things. First, the order of the members in the PPLC, and then the path to take in  $G$  between each pair of consecutive members in the PPLC. Since we are minimizing the number of lightpaths (or links, since a lightpath can only span a single physical link), then the shortest path would be the obvious choice for the second part of the problem. The first part, however, (ordering the members) is what makes

```

1 Algorithm 1. VTTR Heuristic: NSOWDM Network
   input : WDM network topology  $G(V, E)$ ,  $K$  many-to-many session requests.
   output: Virtual Topology ( $VT$ ), Routing of the  $K$  sessions on  $VT$ .
2 sort sessions in a list  $S$  in a descending order in terms of  $((N_{s_k} - 1)t_{s_k})\%g$ .
3 for each session  $s_k$  in the sorted list  $S$  do
4   | order members in  $m_{s_k}$  according to the (NN) Algorithm where the nearest member from the
   | current member is the one who has the shortest distance in  $G$  from the current member.
   | The first member is selected randomly.
5   for  $i = 0, 1, \dots, |m_{s_k}| - 1$  do
6   |   | provision as much traffic as possible out of the  $(N_{s_k} - 1)t_{s_k}$  traffic units between
6   |   | members  $m_{s_k}[i]$  and  $m_{s_k}[i + 1]$  using the current virtual topology ( $VT$ ).
7   |   | for the remaining unprovisioned traffic  $t'$  (if any), establish  $\lceil \max(0, t' - c_{\vec{e}}) / g \rceil$ 
7   |   | lightpaths on each link  $\vec{e}$  on the shortest path between members  $m_{s_k}[i]$  and  $m_{s_k}[i + 1]$ 
7   |   | in  $G$ , where the cost of a link  $\vec{e}$  in  $G$  is  $\lceil \max(0, t' - c_{\vec{e}}) / g \rceil$ .
8   | end
9 end

```

the problem hard. A very similar problem that requires this kind of hard ordering is the well-known traveling salesman problem (TSP). We map our problem to the TSP as follows. Each member in  $m_{s_k}$  corresponds to a city in the TSP instance, and the cost of traveling between two cities is the number of links on the shortest path between the corresponding members in  $G$ . Finding a least cost tour in the TSP instance becomes equivalent to finding a MIN-PPLC for  $s_k$  in  $G$ . One of the simplest and yet powerful heuristics for the TSP is the Nearest Neighbor (NN) Algorithm, where a random member is first selected and the next member is the one with the shortest distance from the current one in  $G$ . This process is repeated until we cover all the members and determine a PPLC for that session.

Given  $K$  many-to-many session requests, the heuristic tries to build a virtual topology (which is initially empty) to accommodate the  $K$  sessions with the minimum number of lightpaths or transceivers. The current virtual topology is represented in the heuristic as a directed graph  $VT$  with a set of nodes that includes every node in  $G$  that at least has one lightpath incoming or outgoing. A directed edge  $\vec{e}$  in  $VT$  exists if there is at least one lightpath on link  $\vec{e}$  in  $G$ . Each directed edge  $\vec{e}$  in  $VT$  has a capacity  $c_{\vec{e}}$  representing the remaining capacity on lightpaths on link  $\vec{e}$  in  $G$ . Note that the  $VT$  graph in a NSOWDM network is a subgraph of the WDM network topology  $G$  since lightpaths can only span a single physical link.

The heuristic (shown in Algorithm 1) has three main steps. First, it sorts sessions in a list  $S$  in a descending order in terms of  $((N_{s_k} - 1)t_{s_k})\%g$  (line 2). Second, for each session  $s_k$  in the sorted list  $S$ , it orders members in  $m_{s_k}$  according to the NN Algorithm (lines 3-4). Note that this is the order of the members in the sessions' PPLCs. Finally, for each session  $s_k$ , it provisions the  $(N_{s_k} - 1)t_{s_k}$  traffic units between each pair of consecutive members in the ordered  $m_{s_k}$  (lines 5-8). The heuristic attempts to provision as much traffic as possible out of the  $(N_{s_k} - 1)t_{s_k}$  traffic units using the existing current virtual topology  $VT$  (line 6). This is done by running a max-flow algorithm (Push-relabel with FIFO vertex selection rule (43)) between the two members in  $VT$  (with edge capacities  $\lfloor c_{\vec{e}}/t_{s_k} \rfloor$ ). Note that by setting the edge capacities in the max-flow instance to  $\lfloor c_{\vec{e}}/t_{s_k} \rfloor$ , we guarantee that the  $t_{s_k}$  traffic units originating from a member will not bifurcate among different routes on  $VT$ . For the remaining unprovisioned traffic  $t'$  (if any), the heuristic establishes  $\lceil \max(0, t' - c_{\vec{e}}) / g \rceil$  lightpaths on each link  $\vec{e}$  on the shortest path between the two members in  $G$  (line 7). Note that the shortest path here corresponds to the path that requires the fewest number of lightpaths to accommodate  $t'$  since the cost of a link  $\vec{e}$  in  $G$  reflects how many new lightpaths are needed to accommodate  $t'$  on  $\vec{e}$ .

*Example:* consider the 6-node network shown in Fig. 4.1 with three many-to-many sessions  $s_1$ ,  $s_2$  and  $s_3$  each with a set of members  $m_{s_1} = \{A, B, E, F\}$ ,  $m_{s_2} = \{B, C, D\}$  and  $m_{s_3} = \{A, B\}$ , respectively. For the sake of this example, let's assume that  $t_{s_1} = 1$ ,  $t_{s_2} = 2$ ,  $t_{s_3} = 3$  and  $g = 8$ . The heuristic first sorts sessions as follows  $S = \{s_2, s_1, s_3\}$ . Then, it orders members in session  $s_2$  as follows  $m_{s_2} = \{B, C, D\}$ , and then establishes lightpaths  $B \rightarrow C$ ,  $C \rightarrow E$ ,  $E \rightarrow D$  and  $D \rightarrow B$  each carrying four units of traffic (PPLC for  $s_2 = \{B - C - E - D - B\}$ ). The heuristic then orders members in session  $s_1$  as follows  $m_{s_1} = \{A, B, F, E\}$ . It then establishes lightpaths  $A \rightarrow B$ ,  $C \rightarrow F$ ,  $F \rightarrow E$  and  $D \rightarrow A$  each carrying three units of traffic and provisions three units of traffic on lightpaths  $B \rightarrow C$  and  $E \rightarrow D$  which will now carry seven units of traffic (PPLC for  $s_1 = \{A - B - C - F - E - D - A\}$ ). Finally, the heuristic orders members in session  $s_3$  as follows  $m_{s_3} = \{A, B\}$ . It then establishes lightpath  $B \rightarrow A$  carrying three units of traffic and provisions three units of traffic on lightpath  $A \rightarrow B$  which will now

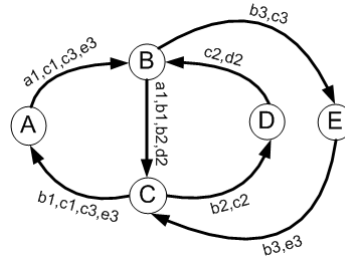


Figure 4.7 Optimal provisioning of many-to-many sessions  $s_1$ ,  $s_2$  and  $s_3$  where  $m_{s_1} = \{A, B, C\}$  each with one traffic unit denoted as  $a1, b1, c1$  and  $m_{s_2} = \{B, C, D\}$  each with one traffic unit denoted as  $b2, c2, d2$  and  $m_{s_3} = \{B, C, E\}$  each with one traffic unit denoted as  $b3, c3, e3$  in a NSTWDM network case ( $g = 4$ ).

carry six units of traffic (PPLC for  $s_3 = \{A - B - A\}$ ). This results in 9 lightpaths (18 transceivers).

### 4.3.2 Heuristic Algorithm for NSTWDM Networks

After careful examination of the MILP results for small sized instances of the problem and for multiple sessions, we have noticed that many-to-many sessions in NSTWDM networks tend to be provisioned through lightpath cycles where, for each session  $s_k$ ,  $(N_{s_k} - 1)t_{s_k}$  traffic units are groomed between each pair of consecutive members in the lightpath cycles. Since a lightpath may groom traffic from different sessions and not just traffic from different members within the same session, lightpath cycles of different sessions are correlated and may share lightpaths. Also, a lightpath cycle for a session  $s_k$  may not be transparent (i.e., number of lightpaths in the lightpath cycle for  $s_k$  may be  $> N_{s_k}$ ). Fig. 4.7 clarifies these points by illustrating the optimal provisioning of three many-to-many sessions  $s_1$ ,  $s_2$  and  $s_3$  each with a set of members  $m_{s_1} = \{A, B, C\}$ ,  $m_{s_2} = \{B, C, D\}$  and  $m_{s_3} = \{B, C, E\}$ , respectively in a NSTWDM network case ( $g = 4$ ). Note that the TLC for  $s_1$  ( $A - B - C - A$ ) and the TLC for  $s_2$  ( $B - C - D - B$ ) share lightpath  $B \rightarrow C$ , while the TLC for  $s_1$  and the lightpath cycle for  $s_3$  ( $B - E - C - A - B$  which is not transparent) share lightpaths  $C \rightarrow A$  and  $A \rightarrow B$ . For example, the lightpath  $B \rightarrow C$  grooms the two traffic units  $a1, b1$  belonging to session  $s_1$  and the two traffic units  $b2, d2$  belonging to session  $s_2$ , while the lightpath  $C \rightarrow A$  grooms the two

traffic units  $b1, c1$  belonging to session  $s_1$  and the two traffic units  $c3, e3$  belonging to session  $s_3$ .

The heuristic we propose for the VTTR problem in NSTWDM networks is based on the observation that many-to-many sessions tend to be provisioned through lightpath cycles which may not be transparent. The heuristic also takes the correlation (sharing of lightpaths) between lightpath cycles of different sessions into account. Given  $K$  many-to-many session requests, the heuristic tries to build a virtual topology (which is initially empty) to accommodate the  $K$  sessions with the minimum number of lightpaths or transceivers. The current virtual topology is represented in the heuristic as a directed graph  $VT$  with a set of nodes that includes every node in  $G$  that at least has one lightpath incoming or outgoing. A directed edge from node  $i$  to node  $j$  exists in  $VT$  if there exists at least one lightpath from node  $i$  to node  $j$  in  $G$ . Each edge  $(i, j)$  in  $VT$  has a capacity  $c_{ij}$  representing the remaining capacity on lightpaths from node  $i$  to node  $j$  in  $G$ . Note that the  $VT$  graph in a NSTWDM network is not necessarily a subgraph of the WDM network topology  $G$  since a lightpath can be established between any two nodes and not just between physically connected nodes as in the NSOWDM network.

The heuristic (shown in Algorithm 2) has three main steps. First, it sorts sessions in a list  $S$  in a descending order in terms of  $((N_{s_k} - 1)t_{s_k})\%g$  (line 2). Second, for each session  $s_k$ , it orders members in  $m_{s_k}$  (lines 3-6). Note that this is the order of the members in the sessions' lightpath cycles. The way the heuristic orders members in a session  $s_k$  is by first separating members in  $m_{s_k}$  into two disjoint sets  $\mathcal{O}$  and  $\mathcal{N}$  (see Algorithm 2 line 4 for their definitions). Afterwards, it orders members in the  $\mathcal{O}$  set according to the NN Algorithm by minimizing the logical hop distance between each pair of consecutive members, while it orders members in the  $\mathcal{N}$  set according to the NN Algorithm by minimizing the physical hop distance between each pair of consecutive members (see Procedure 1). The third and last step of the heuristic is the provisioning of the  $(N_{s_k} - 1)t_{s_k}$  traffic units between each pair of consecutive members in the ordered  $m_{s_k}$  (lines 7-24). Between each pair of consecutive members in the  $\mathcal{O}$  set, the heuristic attempts to provision as much traffic as possible out of the  $(N_{s_k} - 1)t_{s_k}$

```

1 Algorithm 2. VTTR Heuristic: NSTWDM Network
   input :  $K$  many-to-many session requests
   output: Virtual Topology  $VT$ , Routing of the  $K$  sessions on  $VT$ 
2 sort sessions in a list  $S$  in a descending order in terms of  $((N_{s_k} - 1)t_{s_k})\%g$ .
3 for each session  $s_k$  in the sorted list  $S$  do
4   Separate members in  $m_{s_k}$  into two disjoint sets, one set  $\mathcal{O}$  that includes members that
   already exist in  $VT$  and another set  $\mathcal{N}$  that includes the remaining members that do not
   exist in  $VT$ .
5    $order(\mathcal{O})$ .
6    $order(\mathcal{N})$ .
7   for  $(i = 0, 1, \dots, |\mathcal{O}| - 2)$  do
8     provision as much traffic as possible out of the  $(N_{s_k} - 1)t_{s_k}$  traffic units between
     members  $\mathcal{O}[i]$  and  $\mathcal{O}[i + 1]$  using the current virtual topology ( $VT$ ).
9     for the remaining unprovisioned traffic  $t'$  (if any), establish  $\lceil t'/g \rceil$  lightpaths between
     members  $\mathcal{O}[i]$  and  $\mathcal{O}[i + 1]$ .
10  end
11  for  $(i = 0, 1, \dots, |\mathcal{N}| - 2)$  do
12    establish  $H_{s_k}$  lightpaths between members  $\mathcal{N}[i]$  and  $\mathcal{N}[i + 1]$ 
13  end
14  if  $(|\mathcal{O}| = 0)$  then
15    establish  $H_{s_k}$  lightpaths between members  $\mathcal{N}[|\mathcal{N}| - 1]$  and  $\mathcal{N}[0]$ .
16  end
17  else
18    if  $(|\mathcal{N}| = 0)$  then
19      establish  $H_{s_k}$  lightpaths between members  $\mathcal{O}[|\mathcal{O}| - 1]$  and  $\mathcal{O}[0]$ .
20    end
21    else
22      establish  $H_{s_k}$  lightpaths between members  $\mathcal{O}[|\mathcal{O}| - 1]$  and  $\mathcal{N}[0]$  and  $H_{s_k}$  lightpaths
      between members  $\mathcal{N}[|\mathcal{N}| - 1]$  and  $\mathcal{O}[0]$ .
23    end
24  end
25 end

```

traffic units using the current virtual topology  $VT$  (line 8). This is done by running a max-flow algorithm between the two members in the current  $VT$  (with edge capacities  $\lfloor c_{ij}^{\rightarrow}/t_{s_k} \rfloor$ ). For the remaining unprovisioned traffic  $t'$  (if any), the heuristic establishes  $\lceil t'/g \rceil$  lightpaths between the two members (line 9). Between each pair of consecutive members in the  $\mathcal{N}$  set, the heuristic (lines 11-12) establishes  $H_{s_k}$  lightpaths to provision the  $(N_{s_k} - 1)t_{s_k}$  traffic units (after this step, members in  $\mathcal{N}$  will be added to  $VT$ ). Finally, the heuristic completes the cycle for each session  $s_k$  by connecting the  $\mathcal{O}$  set and the  $\mathcal{N}$  set by  $H_{s_k}$  lightpaths at both ends (line 14-24).

*Example:* We consider the same example in Section 4.3.1 of the 6-node network shown in

```

1 Procedure 1. order( $\mathcal{X}$ )
2 select a member in  $\mathcal{X}$  randomly as the current member.
3 while there is at least one unselected member in  $\mathcal{X}$  do
4   Case 1:  $\mathcal{X} = \mathcal{O}$ 
5     select the next member (from the remaining unselected members) as the member
       who has the shortest logical distance in  $VT$  from the current member.
6   Case 2:  $\mathcal{X} = \mathcal{N}$ 
7     select the next member (from the remaining unselected members) as the member
       who has the shortest physical distance in  $G$  from the current member.
8   current member=next member.
9 end

```

Fig. 4.1 and the three many-to-many session requests, except that the 6-node network is now a NSTWDM network. The heuristic first sorts sessions as follows  $S = \{s_2, s_1, s_3\}$ . Afterwards, it orders members in session  $s_2$  as follows  $m_{s_2} = \{B, C, D\}$  where all members belong to the  $\mathcal{N}$  set. The heuristic then establishes lightpaths  $B \rightarrow C$ ,  $C \rightarrow D$  and  $D \rightarrow B$  each carrying four units of traffic (TLC for  $s_2 = \{B - C - D - B\}$ ). The heuristic then orders members in session  $s_1$  as follows  $m_{s_1} = \{B, A, E, F\}$ , where member  $B$  belongs to the  $\mathcal{O}$  set and members  $A, E$  and  $F$  belong to the  $\mathcal{N}$  set. It then establishes lightpaths  $B \rightarrow A$ ,  $A \rightarrow E$ ,  $E \rightarrow F$  and  $F \rightarrow B$  each carrying three units of traffic (TLC for  $s_1 = \{B - A - E - F - B\}$ ). Finally, the heuristic orders members in session  $s_3$  as follows  $m_{s_3} = \{A, B\}$  where members  $A$  and  $B$  belong to the  $\mathcal{O}$  set. It then provisions three units of traffic on lightpaths  $A \rightarrow E$ ,  $E \rightarrow F$ ,  $F \rightarrow B$  and  $B \rightarrow A$  which will now carry six units of traffic (lightpath cycle for  $s_3 = \{A - E - F - B - A\}$ ). Note that the lightpath cycle for session  $s_3$  is not transparent since it consists of more than two lightpaths. This results in 7 lightpaths (14 transceivers).

### 4.3.3 Heuristic Algorithm for SHWDM Networks

In this heuristic algorithm, we assume that the three observations stated in Section 4.2.2 (the restricted MILP for SHWDM networks) always hold. Therefore, the hub for a session can only be selected from its set of members and the traffic from a member to the hub in the members-to-hub journey of a session traverses a single direct lightpath from the member to the hub and finally, for each session  $s_k$ , there are  $H_{s_k}$  downstream light-trees that only groom the linear combinations for  $s_k$ . Assuming that these observations always hold, selecting the



```

1 Algorithm 3. VTTR Heuristic: SHWDM Network
   input :  $K$  many-to-many session requests
   output: The hub for each session
2 for (each member  $l \in \bigcup_{s_k} m_{s_k}$ ) do
3   | count the number of appearances of  $l$  in all the  $K$  sessions.
4 end
5 for each session  $s_k$  do
6   | select the hub for  $s_k$  as the element in  $\bigcup_{s_k} m_{s_k}$  that is a member in  $m_{s_k}$  and has the largest
   | number of appearances in all the  $K$  sessions.
7 end

```

hub for each session determines what lightpaths and light-trees to establish and how to route and groom traffic on them, and therefore it solves the VTTR problem.

The heuristic we propose (shown in Algorithm 3) selects the same hub node for as many sessions as possible. It starts by counting the total number of appearances of each member in  $\bigcup_{s_k} m_{s_k}$  in all the  $K$  sessions (lines 2-4). Then, it selects the hub node for each session  $s_k$  as the element in  $\bigcup_{s_k} m_{s_k}$  that is a member in  $m_{s_k}$  and has the largest number of appearances in all the  $K$  sessions (lines 5-7). Selecting the same hub for as many sessions as possible increases the likelihood of inter-session grooming on the upstream direction, which has a direct impact on reducing the number of lightpaths or transceivers needed.

*Example:* We consider the same example in Section 4.3.1 of the 6-node network shown in Fig. 4.1 and the three many-to-many session requests, except that the 6-node network is now a SHWDM network. The heuristic first counts the total number of appearances of each member in  $\bigcup_{s_k} m_{s_k} = \{A, B, C, D, E, F\}$  in the three sessions as follows  $\{A = 2, B = 3, C = 1, D = 1, E = 1, F = 1\}$ . Afterwards, the heuristic selects the hub for sessions  $s_1$ ,  $s_2$  and  $s_3$  as follows  $\text{hub}(s_1) = B$ ,  $\text{hub}(s_2) = B$  and  $\text{hub}(s_3) = B$ . Based on this hub selection, there will be three upstream lightpaths for  $s_1$  ( $A \rightarrow B$ ,  $E \rightarrow B$  and  $F \rightarrow B$ ) each carrying one unit of traffic and one light-tree ( $B \rightarrow \{A, E, F\}$ ) carrying three units of traffic. For session  $s_2$ , there will be two upstream lightpaths ( $C \rightarrow B$  and  $D \rightarrow B$ ) each carrying two units of traffic and one light-tree ( $B \rightarrow \{C, D\}$ ) carrying four units of traffic. Finally, for session  $s_3$ , three units of traffic are provisioned on the lightpath  $A \rightarrow B$  which will now carry four units of traffic and a light-tree ( $B \rightarrow \{A\}$  which is simply a lightpath) is established carrying three units of traffic.

This results in six lightpaths and two light-trees (19 transceivers).

#### 4.3.4 Complexity Analysis

The time complexity of Algorithms 1 and 2 is dominated by the step of finding the max-flow using the Push-relabel Algorithm with FIFO vertex selection rule that has a time complexity of  $O(N^3)$ . This step is repeated for each member for each session, which drives the time complexity of Algorithms 1 and 2 to  $O(KN^4)$ . Finally, the time complexity of Algorithm 3 is  $O(KN)$ .

#### 4.3.5 Routing and Wavelength Assignment

Once we solve the VTTR problem and determine the virtual topology, we can then consider the RWA problem. In this problem, we need to provision each of the optical channels determined by the VTTR problem on the optical WDM network by determining: 1) the route of each optical channel on the optical WDM network, and 2) the wavelength to assign to each optical channel, while taking the wavelength continuity constraint into account. The objective of the RWA is to minimize the total number of wavelengths used ( $W \leq W_{max}$ ).

The RWA problem has been extensively studied in the literature and it has been proven to be NP-complete. Many heuristics have been proposed for both the routing and the wavelength assignment problems. For example, fixed routing, fixed-alternate routing, and adaptive routing are some of the well-known approaches for routing, while first fit, least used, and most used are some of the well-known approaches for wavelength assignment. For a review on routing and wavelength assignment approaches, the reader is referred to (44).

Since the RWA problem has been extensively studied, we are only interested in comparing the proposed WDM networks in terms of their consumption of wavelengths. To make the comparison fair and to base it on the merit of the networks only, we use very simple approaches for routing and wavelength assignment. We use fixed shortest path routing and first fit wavelength assignment for lightpaths, while we use fixed shortest path tree routing and first fit wavelength assignment for light-trees. The detailed description of the heuristic is shown in Algorithm 4.

```

1 Algorithm 4. RWA Heuristic
2 for each lightpath/light-tree do
3   compute its shortest-path/shortest-path-tree on  $G$ .
4   for  $w=1,2,\dots,W_{max}$  do
5     if  $w$  is free on all links traversed by the shortest-path/shortest-path-tree then
6       route the lightpath/light-tree on its shortest-path/shortest-path-tree and assign it
7       wavelength  $w$ 
8     end
9   end
10 if all lightpaths/light-trees are successfully routed then
11   return the largest  $w$  used.
12 end
13 else
14   return no feasible RWA found.
15 end

```

#### 4.3.6 Numerical Results

To verify the accuracy of our proposed heuristic algorithms for NSOWDM, NSTWDM and SHWDM networks, we conduct a number of experiments on small and medium sized networks. Ten experiments (i.e., problem instances) are conducted on the 6-node network shown in Fig. 4.4.(a), while another ten are conducted on the Abilene research network shown in Fig. 3.1 in Chapter 3. Each of the 20 experiments has 10 many-to-many session requests, where the size of each session is randomly selected between  $[2,5]$ . For the 6-node experiments, a member in a session is randomly selected between  $[0,5]$ , while for the Abilene research network experiments it is randomly selected between  $[0,9]$ . Finally, traffic demand of members in a session, in all the 20 experiments, is randomly selected between  $[1,16]$  ( $g = 16$ ).

The optimal solution for each experiment is obtained in each of the NSOWDM, NSTWDM and SHWDM networks by solving the corresponding MILP using the CPLEX solver (45). We have also obtained solutions for each experiment in each of the three networks by solving the corresponding heuristic. We define the *normalized number of transceivers* ( $R/R_{opt}$ ) as the ratio of the number of transceivers obtained by a heuristic ( $R$ ) over the optimal number of transceivers obtained by its corresponding MILP ( $R_{opt}$ ). Fig. 4.8 shows the values of  $R/R_{opt}$

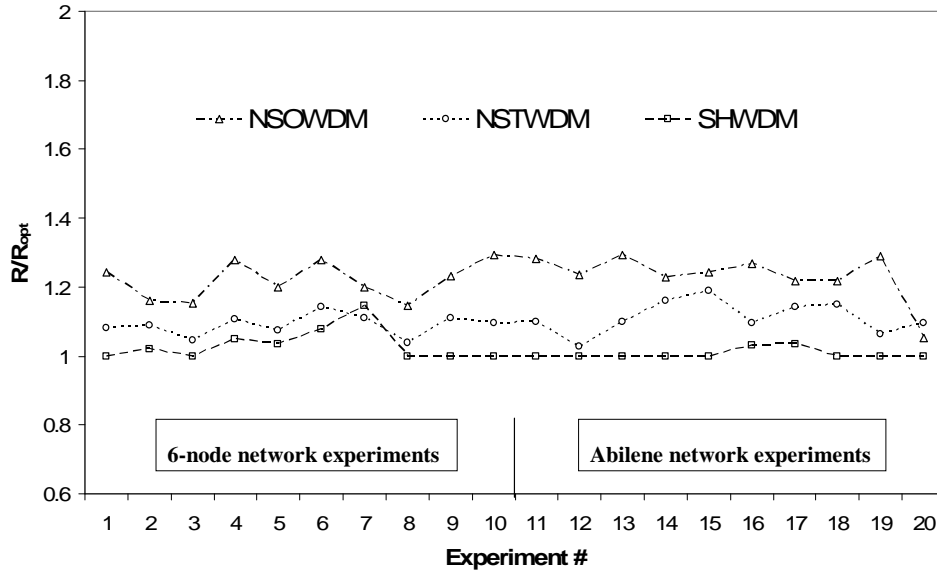


Figure 4.8 Values of  $R/R_{opt}$  for the 20 experiments conducted on the 6-node network (exps 1-10) and on the Abilene research network (exps 11-20) for each of NSOWDM, NSTWDM and SHWDM networks.

for the 20 experiments conducted on the 6-node network and on the Abilene research network for each of NSOWDM, NSTWDM and SHWDM network cases.

We can see from the figure that solutions obtained from the heuristics for NSOWDM, NSTWDM and SHWDM networks either match or are very close to their corresponding optimal solutions (at most 29% above the optimal). Also, this closeness between the optimal and the heuristic has been consistent across all the 20 experiments on both the 6-node network and the Abilene research network.

Next, we compare the four WDM networks in terms of the costs  $R$  and  $W$ . Since the grooming capabilities of the four networks are greatly varied, their performance will be dependent on traffic granularities of sessions in the network. Therefore, we should compare them for different traffic granularities. To make this comparison, we assume a static uniform traffic with all sessions in an experiment having the same traffic demand  $t$  (e.g.,  $t_{s_1} = t_{s_2} = \dots = t_{s_K} = t$ ), where  $1 \leq t \leq g$ .

Since optimal values of  $R$  in NSOWDM, NSTWDM and SHWDM networks are not possible to obtain for large sized instances of the problem, we will conduct two sets of experiments. One

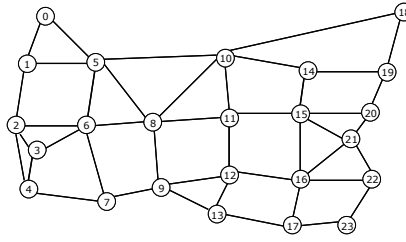


Figure 4.9 The USNET network

set of small experiments are conducted on the 6-node network Fig. 4.4.(a) in which optimal values of  $R$  are obtained by solving the corresponding MILPs using the CPLEX solver. Another set of large experiments are conducted on the USNET network, shown in Figure 4.9, in which values of  $R$  are obtained using the corresponding heuristics.

1) *Small network Example:* In this example, eight randomly generated experiments are conducted on the 6-node network shown in Fig. 4.4.(a). The number of sessions in each experiment is randomly selected between  $[4,6]$ . The size of each session is randomly selected between  $[2,5]$ , while a member in a session is randomly selected between  $[0,5]$ . Assuming the static uniform traffic, each of the eight experiments is conducted for each value of  $t = 1, 2, \dots, g$  ( $g = 16$ ) on all the four networks. We define  $\bar{R}$  to be the average value of all  $R$  values obtained from the eight experiments at a particular value of  $t$  on a certain network. The resulting values of  $\bar{R}$  are shown in Fig. 4.10.(a).

After determining the optical channels for each experiment at each value of  $t$  on each network, these channels are routed and assigned a wavelength according to Algorithm 4. We also define  $\bar{W}$  to be the average value of all  $W$  values obtained from the eight experiments at a particular value of  $t$  on a certain network. The resulting values of  $\bar{W}$  are shown in Fig. 4.10.(b).

In relatively small networks, where optimal values of  $R$  on the NSOWDM, NSTWDM, and SHWDM networks can be obtained by solving the corresponding MILP, we draw the following conclusions from Figs. 4.10.(a)-(b):

- *In terms of the cost  $R$ :* NSTWDM networks are the most cost-effective choice for low traffic granularities ( $1 \leq t \leq 3g/8$ ), while SHWDM networks are the most cost-effective

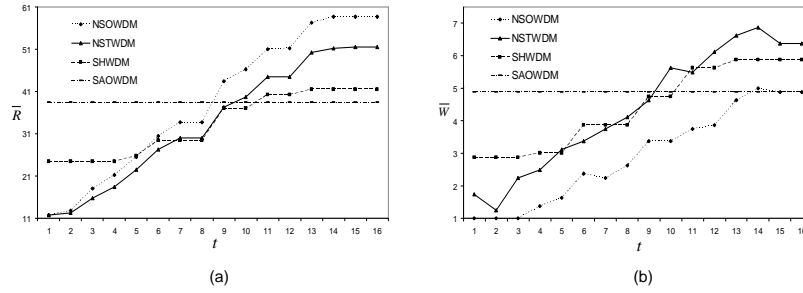


Figure 4.10 (a): Values of  $\bar{R}$  for  $t = 1, 2, \dots, g$  on the 6-node network for  $g = 16$ . (b): Values of  $\bar{W}$  for  $t = 1, 2, \dots, g$  on the 6-node network for  $g = 16$

choice when traffic granularities lie in the middle ( $3g/8 < t \leq 5g/8$ ). Finally, for high traffic granularities ( $t > 5g/8$ ), SAOWDM networks are the most cost-effective choice.

- *In terms of the cost  $W$ :* NSOWDM networks are the most cost-effective choice for all the traffic granularities spectrum ( $1 \leq t \leq g$ ). SAOWDM networks are also a cost-effective choice for high traffic granularities ( $t > 3g/4$ ).

2) *Large network Example:* In this example, 100 randomly generated experiments, each with 80 many-to-many session requests, are conducted on the USNET network shown in Fig. 4.9. The size of a session in an experiment is randomly selected between  $[2, 24]$ , while a member in a session is randomly selected between  $[0, 23]$ . Assuming the static uniform traffic, each of the 100 experiments is conducted for each value of  $t = \{1, 3, 9, 12, 18, 24, 36, 48, 96, 192\}$  ( $g = 192$ ) on all the four networks. The first eight values of  $t$  represent the recommended rates for OC streams. The resulting values of  $\bar{R}$ , which is defined as before, are shown in Fig. 4.11.(a).

After determining the optical channels for each experiment at each value of  $t$  on each network, these channels are routed and assigned a wavelength according to Algorithm 4. The resulting values of  $\bar{W}$ , which is defined as before, are shown in Fig. 4.11.(b).

In relatively large networks, where values of  $R$  on the NSOWDM, NSTWDM and SHWDM are obtained using the corresponding heuristic, we draw the following conclusions from Fig. 4.11.(a)-(b):

- *In terms of the cost  $R$ :* NSTWDM networks are the most cost-effective choice for very low

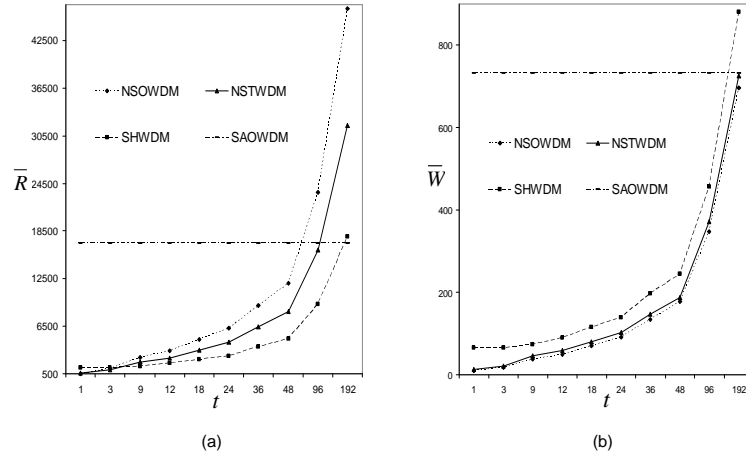


Figure 4.11 (a): Values of  $\bar{R}$  for  $t = \{1, 3, 9, 12, 18, 24, 36, 48, 96, 192\}$  on USNET for  $g = 192$ . (b): Values of  $\bar{W}$  for  $t = \{1, 3, 9, 12, 18, 24, 36, 48, 96, 192\}$  on USNET for  $g = 192$

Table 4.8 Values of  $\overline{R_{saved}}$  and  $\overline{R_{saved}}/\bar{R}$  for the USNET experiments

$t$	1	3	9	12	18	24	36	48	96	192
$\overline{R_{saved}}$	0	0	73.9	60.2	114.6	92	194.2	230.2	505.6	1036.5
$\overline{R_{saved}}/\bar{R}$	0%	0%	5.1%	3.3%	5%	3.3%	4.9%	4.7%	5.5%	5.8%

traffic granularities ( $1 \leq t < g/16$ ), while SAOWDM networks are the most cost-effective for very high traffic granularities ( $t > 15g/16$ ). SHWDM networks, on the other hand, are the most cost-effective choice for a large portion of the traffic granularities spectrum ( $g/16 \leq t \leq 15g/16$ ).

- *In terms of the cost  $W$* : NSOWDM networks are the most cost-effective choice for the whole traffic granularities spectrum ( $1 \leq t \leq g$ ).

Although NSTWDM networks are the most cost-effective choice only for ( $1 \leq t < g/16$ ), this part of the traffic granularities spectrum is of practical interest in traffic grooming especially when  $g$  is relatively high. For example, many applications request only OC-1 and OC-3 circuits, while the capacity of a wavelength channel (grooming factor) is OC-192. On the other extreme of the traffic granularities spectrum ( $t > 15g/16$ ), SAOWDM networks are the most cost-effective choice. This part of the spectrum is also of practical interest for many applications whose bandwidth demands almost fill the capacity of an optical channel. Finally, SHWDM

networks through the novel use of network coding, are the most cost-effective for a large portion of the traffic granularities spectrum ( $g/16 \leq t \leq 15g/16$ ).

Table 4.8 illustrates the advantage of network coding in reducing the number of transceivers in SHWDM networks by showing the values of  $\overline{R_{saved}}$ , which is defined as the average value of all  $R_{saved}$  values obtained from the 100 USNET experiments at a particular value of  $t$  on the SHWDM network. The table also shows the corresponding percentage savings due to the use of network coding ( $\overline{R_{saved}}/\overline{R}$ ).

#### 4.4 Chapter Summary

In this chapter, we introduced heuristic solutions for the many-to-many traffic grooming problem in each of the four WDM networks. First, we introduced *lightpath cycles* as the optimal virtual topology for a number of special cases in NSOWDM and NSTWDM networks. Then, based on observations from the optimal solution in each of the NSTWDM and the SHWDM networks, we restricted the solution space of the corresponding MILPs to obtain near-optimal solutions in a much shorter time. Finally, we introduced efficient near-optimal heuristic algorithms for the many-to-many traffic grooming problem in each of the four WDM networks. We concluded that each of the four networks is the most cost-effective choice for a certain range of traffic granularities.



## CHAPTER 5. BOUNDS AND APPROXIMATION ALGORITHMS

In this chapter, we derive bounds and develop approximation algorithms for the many-to-many traffic grooming problem in NSTWDM networks. Although the MILP formulations introduced in Chapter 3 guarantee an optimal solution, they have an exponential time complexity. In addition, the heuristic solutions introduced in Chapter 4, while efficient, have no guarantee on the quality of the solution. Therefore, there is a need to develop efficient polynomial-time algorithms that guarantee the quality of the solution, and this is the objective of this chapter. We only consider NSTWDM networks that only support lightpaths which may span multiple physical links. Since a transceiver is needed for each initiation and termination of a lightpath (i.e, each lightpath requires two transceivers), the objective of the many-to-many traffic grooming problem becomes to minimize the total number of lightpaths established. Regarding notation, we use exactly the same notation provided in Table 3.1 in Chapter 3, and all new symbols used in this chapter are shown in Table 5.1.

The rest of the chapter is organized as follows. In Section 5.1, we derive lower and upper bounds on the number of lightpaths needed to provision a set of many-to-many traffic demands. In Section 5.2, we develop two novel approximation algorithms for the many-to-many traffic grooming problem. In Section 5.3, we evaluate the performance of the two algorithms on three other objectives besides the number of lightpaths, including the number of logical hops traversed by a traffic stream, total amount of electronic switching, and Min-Max objectives. In Section 5.4, we address the routing and wavelength assignment (RWA) problem. In Section 5.5, we conduct extensive experiments to evaluate and compare the performance of the two algorithms on the various objectives mentioned in the chapter including the number of wavelengths used. In Section 5.6, we summarize the chapter.

Table 5.1 List of symbols used in the chapter

Symbol	Definition
$k_i$	number of sessions where node $i$ is a member.
$N_{min}$	minimum session size among all the $K$ sessions.
$t_{min}$	minimum traffic demand among all the $K$ sessions.
$S_i$	set of sessions where node $i$ is a member ( $k_i =  S_i $ ).
$S_{ij}$	set of sessions where both nodes $i$ and $j$ are members.
$S_{iFj}$	set of sessions where member $i$ follows member $j$ immediately in the session's TLCs.
$P_{ij}$	total number of lightpaths from node $i$ to node $j$ .
$P$	total number of lightpaths in the network ( $P = \sum_{i,j} P_{ij}$ ).
$rem_{ij}$	remaining unused capacity on lightpaths from $i$ to $j$ if we place $j$ after $i$ in the TLCs for all sessions in the set $S_{ij}$ .
$l_{Alg^x}^{s_k,ij}$	the number of logical hops traversed by the traffic stream originating from member $i \in m_{s_k}$ and destined to member $j \in m_{s_k}$ according to Algorithm $x$ .
$l_{Alg^x}^{s_k,i}$	the average number of logical hops traversed by a traffic stream originating from member $i \in m_{s_k}$ according to Algorithm $x$ .
$l_{Alg^x}^{s_k}$	the average number of logical hops traversed by a traffic stream in session $s_k$ according to Algorithm $x$ .
$l_{Alg^x}$	the average number of logical hops traversed by a traffic stream in any of the $K$ sessions according to Algorithm $x$
$e_{Alg^x}^i$	the total amount of electronic switching at node $i$ according to Algorithm $x$ .
$e_{Alg^x}$	the total amount of electronic switching in the whole network (at all nodes) according to Algorithm $x$ .
$P_{max}^{Alg^x}$	maximum number of lightpaths incoming or outgoing at a node according to Algorithm $x$ .
$e_{max}^{Alg^x}$	maximum amount of electronic switching at a node according to Algorithm $x$ .

## 5.1 Bounds

In this section, we derive bounds on the total number of lightpaths needed to accommodate a set of many-to-many traffic demands. We start by deriving a lower bound that is independent of any grooming algorithm, and then we derive an upper bound by considering the worst case scenario where no traffic grooming is performed.

### 5.1.1 A Lower Bound

We derive a lower bound on the number of lightpaths required by considering each node in the network separately. The minimum number of lightpaths incoming to a node  $i$  can be found

by counting the total traffic that this node should receive from all sessions  $s_k$  where  $i \in m_{s_k}$ . Let  $S_i$  denotes the set of sessions where node  $i$  is a member (note that  $|S_i| = k_i$ ). The total traffic that node  $i$  should receive is  $\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}$ . Therefore, at least  $\left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil$  lightpaths should be incoming to  $i$  in order to receive this traffic. Summing for all the nodes in the network, we obtain a lower bound  $L$  on the total number of lightpaths required:

$$L = \sum_{i=0}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \quad (5.1)$$

We note that this is just a lower bound on the number of lightpaths and it does not necessarily yield a feasible solution to the many-to-many traffic grooming problem. Next, we obtain an upper bound on the number of lightpaths required by any many-to-many traffic grooming algorithm.

### 5.1.2 An Upper Bound

We consider the worst case scenario where no traffic grooming is performed between any two traffic streams even within the same session. In this case, each node  $i$  will have a direct lightpath incoming from each of the other  $N_{s_k} - 1$  members in the same session  $s_k$  for all sessions  $s_k \in S_i$ . Therefore, the total number of lightpaths  $P$  required according to this worst case scenario is given by:

$$\begin{aligned} P &= \sum_{i=0}^{N-1} \sum_{s_k \in S_i} N_{s_k} - 1 \leq \sum_{i=0}^{N-1} \sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k} \\ &\leq \sum_{i=0}^{N-1} g \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil = gL \end{aligned} \quad (5.2)$$

Since this is the worst case scenario, then it serves as an upper bound for any many-to-many traffic grooming algorithm. Hence, we have the following result:

**Theorem 6.** *Any many-to-many traffic grooming algorithm with any grooming policy is a  $g$ -approximation algorithm.*

Next, we propose two novel approximation algorithms for the many-to-many traffic grooming problem in NSTWDM mesh networks.

## 5.2 Approximation Algorithms

As we stated before, the general many-to-many traffic grooming problem is NP-hard. In this section, we introduce two novel approximation algorithms for the many-to-many traffic grooming problem in NSTWDM mesh networks.

### 5.2.1 Algorithm 1

This algorithm is based on transparent lightpath cycles (TLCs) which was introduced in Section 4.1.2 in Chapter 4. In the algorithm, we assume that many-to-many sessions are always provisioned through TLCs. Although the optimality of TLCs was only for certain special cases (see Section 4.1.2 in Chapter 4), we will show that this assumption generally gives near-optimal solutions. First, let us assume that each session  $s_k$  is provisioned through  $\left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil$  identically ordered TLCs for  $s_k$  and ignore inter-session grooming (TLCs in this case only perform intra-session grooming between members within the same session, see Fig. 4.2.(a) in Chapter 4). In this case, node  $i$  will have  $\left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil$  lightpaths incoming from each session  $s_k \in S_i$ . Hence, the total number of lightpaths  $P$  required according to this algorithm is given by:

$$\begin{aligned}
 P &= \sum_{i=0}^{N-1} \sum_{s_k \in S_i} \left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil \\
 &\leq \sum_{i=0}^{N-1} \left( \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k}-1)t_{s_k}}{g} \right\rceil + k_i \right) \\
 &= L + \sum_{i=0}^{N-1} k_i
 \end{aligned} \tag{5.3}$$

The inequality holds due to the fact that  $\sum_{m=0}^{M-1} \lceil x_m \rceil \leq \left\lceil \sum_{m=0}^{M-1} x_m \right\rceil + M$  for any positive integer  $M$  and positive real values  $x_1, x_2, \dots, x_{M-1}$ .

Now, let's consider the lower bound  $L$  again:

$$\begin{aligned}
 L &= \sum_{i=0}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k}-1)t_{s_k}}{g} \right\rceil \\
 &\geq \sum_{i=0}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{min}-1)t_{min}}{g} \right\rceil
 \end{aligned}$$

$$\begin{aligned}
&\geq \sum_{i=0}^{N-1} \frac{\sum_{s_k \in S_i} (N_{min} - 1)t_{min}}{g} \\
&= \frac{(N_{min} - 1)t_{min}}{g} \sum_{i=0}^{N-1} k_i
\end{aligned} \tag{5.4}$$

Substituting (5.4) in (5.3), we have:

$$\begin{aligned}
P &\leq L + \sum_{i=0}^{N-1} k_i \leq L + \frac{Lg}{(N_{min} - 1)t_{min}} \\
&= \left(1 + \frac{g}{(N_{min} - 1)t_{min}}\right)L
\end{aligned} \tag{5.5}$$

Hence, we have the following result:

**Theorem 7.** *Any many-to-many traffic grooming algorithm that assumes that each session  $s_k$  is provisioned through  $\left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil$  identically ordered TLCs for  $s_k$  is a  $1 + \frac{g}{(N_{min}-1)t_{min}}$  approximation algorithm.*

An interesting case is when  $(N_{min} - 1)t_{min} \geq g$  where we obtain an approximation ratio of at most 2. This relatively good approximation ratio is intuitive since when  $(N_{min} - 1)t_{min} \geq g$ , then each session's traffic efficiently fills at least half of its TLCs. The best approximation ratio we can obtain is when  $N_{min} = N$  and  $t_{min} = g$  where we get an approximation ratio of  $(1 + \frac{1}{(N-1)})$ . On the other extreme, when  $(N_{min} - 1)t_{min}$  is too small (e.g., equals to 1), then we obtain a  $1 + g$  approximation ratio. This is also intuitive since when  $(N_{min} - 1)t_{min} = 1$ , then  $\left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil$  TLCs for each session  $s_k$  may be a significant waste without inter-session grooming.

To further improve this algorithm we still assume that each session  $s_k$  is provisioned through  $\left\lceil \frac{(N_{s_k}-1)t_{s_k}}{g} \right\rceil$  identically ordered TLCs for  $s_k$ . However, we now perform inter-session grooming so that TLCs of different sessions may share lightpaths (i.e., lightpaths may groom traffic from different sessions and not just traffic from different members within the same session). The algorithm performs inter-session grooming as follows. Between each pair of nodes  $i$  and  $j$ , it grooms the  $\sum_{s_k} (N_{s_k} - 1)t_{s_k}$  traffic units for all sessions  $s_k$  where  $i, j \in m_{s_k}$  and member  $j$  follows member  $i$  immediately in the session's TLCs. Note that the order of the members in the TLCs is significant and must be taken into account to make inter-session grooming efficient.

We start by assuming that members are ordered randomly in each session's TLCs. Let  $S_{iFj}$  denotes the set of sessions where member  $i$  follows member  $j$  immediately in the session's TLCs. The total number of lightpaths  $P$  required according to this algorithm is given by:

$$\begin{aligned}
P &= \sum_{i=0}^{N-1} \sum_{j=0; j \neq i}^{N-1} \left\lceil \frac{\sum_{s_k \in S_{iFj}} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \\
&\leq \sum_{i=0}^{N-1} \sum_{j=0; j \neq i}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \\
&= \sum_{j=0}^{N-2} \sum_{i=0}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \\
&= (N - 1)L
\end{aligned} \tag{5.6}$$

The first inequality holds since  $S_{iFj}$  is a subset of  $S_i$ . The exchange of the summations in the second equality is valid since what is inside the inner summation  $\left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil$  is independent of  $j$ . This algorithm so far has an approximation ratio of  $\min\{g, 1 + \frac{g}{(N_{min}-1)t_{min}}, N - 1\}$ . A better approximation ratio can be found by making a more intelligent ordering of the members in each session's TLCs. We first order the nodes in the network in a list according to some criteria (e.g., ascending or descending order). Afterwards, for each session  $s_k$ , we order members in the session's TLCs according to the list of ordered nodes. More precisely, we order members in a session  $s_k$  TLCs by placing the first member as the first node in the list that is a member in session  $s_k$  and the second member as the second node in the list that is a member in session  $s_k$  and so on until we place all the members. Note that the first member immediately follows the last member in the ordered TLCs. Based on this ordering of the members in the sessions' TLCs, we have the following lemma:

**Lemma 8.** *A node  $i$  in Algorithm 1 cannot have direct lightpaths incoming from more than  $N - N_{min} + 1$  other nodes.*

*Proof.* We prove the lemma by proving that the  $N_{min} - 2$  nodes that immediately follow  $i$  in the list of ordered nodes cannot have direct lightpaths outgoing to  $i$  (note that the first node in the list immediately follows the last node in the list). To prove this, we consider any node  $j$  in these  $N_{min} - 2$  nodes. We have two cases for  $j$ . Either  $j$  comes after  $i$  in the list (i.e.,

between  $i$  and the last node in the list) or before  $i$  in the list (i.e., between the first node in the list and  $i$ ).

In the first case when  $j$  comes after  $i$  in the list, the only way that  $j$  could have a direct lightpath outgoing to  $i$  is when  $i$  is the first member in the TLCs for a session and  $j$  is the last one. Since the session size is at least  $N_{min}$  then there should be at least  $N_{min} - 2$  other nodes in the session. Also, since members in the TLCs are ordered according to the list of ordered nodes, then these  $N_{min} - 2$  nodes must be between  $i$  and  $j$  in the list. However, there are at most  $N_{min} - 3$  nodes between  $i$  and  $j$  which makes a contradiction.

In the second case when  $j$  comes before  $i$  in the list, the only way that  $j$  could have a direct lightpath outgoing to  $i$  is when  $j$  immediately precedes  $i$  in the TLCs for a session. This prevents all the nodes between  $j$  and  $i$  in the list (which are at least  $N - (N_{min} - 2) - 1 = N - N_{min} + 1$ ) to be members in the session. Hence, only  $N - (N - N_{min} + 1) - 2 = N_{min} - 3$  nodes are left to be members in the session. However, since the session size is at least  $N_{min}$  then there should be at least  $N_{min} - 2$  other nodes in the session, which makes a contradiction. Therefore, the  $N_{min} - 2$  nodes that immediately follow  $i$  in the list of ordered nodes cannot have direct lightpaths outgoing to  $i$ , which means that  $i$  cannot have direct lightpaths incoming from more than  $N - N_{min} + 1$  other nodes.  $\square$

After this ordering of the members in each session's TLCs, between each pair of nodes  $i$  and  $j$ , Algorithm 1 grooms the  $\sum_{s_k} (N_{s_k} - 1)t_{s_k}$  traffic units for all sessions  $s_k \in S_{jFi}$ . The total number of lightpaths  $P$  required by Algorithm 1 is given by:

$$P = \sum_{i=0}^{N-1} \sum_{j=0; j \neq i}^{N-1} \left\lceil \frac{\sum_{s_k \in S_{iFj}} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil$$

However, from lemma 8,  $j$  cannot take more than  $N - N_{min} + 1$  values and since  $S_{iFj}$  is a subset of  $S_i$ , then we have:

$$\begin{aligned} P &\leq \sum_{i=0}^{N-1} \sum_{j=0}^{N-N_{min}} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \\ &= \sum_{j=0}^{N-N_{min}} \sum_{i=0}^{N-1} \left\lceil \frac{\sum_{s_k \in S_i} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil \end{aligned}$$

```

1 Algorithm 1. Many-to-Many Traffic Grooming: Lightpath Cycles
2 Initialize lists  $\mathcal{U} = \phi$ ,  $\mathcal{Y} = V$ ,  $\mathcal{X}_{s_k} = \phi$  (for all  $1 \leq k \leq K$ ) and counters  $c_1 = 1$  and  $c_2 = 0$ .
3 for each ordered pair of nodes  $(i, j)$  do
4    $rem_{ij} = g - \left( \sum_{s_k \in S_{ij}} (N_{s_k} - 1)t_{s_k} \right) \% g.$ 
5   if  $rem_{ij} = g$  then
6      $rem_{ij} = 0$ 
7   end
8 end
9 select a node  $v \in \mathcal{Y}$  randomly and let  $\mathcal{U}[0] = v$ .
10 remove  $v$  from  $\mathcal{Y}$ .
11 while  $\mathcal{Y}$  is not empty do
12   select a node  $w \in \mathcal{Y}$  that has the smallest  $rem_{vw}$  value.
13    $\mathcal{U}[c_1++] = w$ .
14   remove  $w$  from  $\mathcal{Y}$ .
15    $v = w$ .
16 end
17 for each session  $s_k$ ,  $1 \leq k \leq K$  do
18    $c_2 = 0$ .
19   for  $i = 0, 1, \dots, N - 1$  do
20     if  $\mathcal{U}[i] \in m_{s_k}$  then
21        $\mathcal{X}_{s_k}[c_2++] = \mathcal{U}[i]$ .
22     end
23   end
24 end
25 for each ordered pair of nodes  $(i, j)$  do
26    $P_{ij} = \left\lceil \frac{\sum_{s_k \in S_{jFi}} (N_{s_k} - 1)t_{s_k}}{g} \right\rceil.$ 
27 end

```

$$= (N - N_{min} + 1)L \quad (5.7)$$

Therefore, we have the following result:

**Theorem 9.** Algorithm 1 is a  $\min\{g, 1 + \frac{g}{(N_{min}-1)t_{min}}, N - N_{min} + 1\}$  approximation algorithm.

Note that when  $N_{min} = N$  (i.e., all-to-all communication), then Algorithm 1 guarantees an optimal solution. On the other extreme when  $N_{min} = 2$ , then we are back to the  $\min\{g, 1 + \frac{g}{(N_{min}-1)t_{min}}, N - 1\}$  approximation ratio.

Although any order of the nodes in the network will guarantee the above approximation ratio, Algorithm 1 orders the nodes in a way to make inter-session grooming efficient (the full



description of the algorithm is shown in Algorithm 1). For each ordered pair of nodes  $(i, j)$ , the algorithm computes the  $rem_{ij}$  value (lines 3-8) which represents the remaining unused capacity on lightpaths from  $i$  to  $j$  if we place  $j$  after  $i$  in the TLCs for all sessions in the set  $S_{ij}$ . If this value is low (e.g., close to 0), then placing  $j$  after  $i$  results in an efficient grooming of traffic into lightpaths. However, when this value is high (e.g., close to  $g - 1$ ), then placing  $j$  after  $i$  results in an inefficient grooming where lightpaths are low utilized. The algorithm then orders the nodes in the network in the list  $\mathcal{U}$  (lines 9-16) according to the  $rem_{ij}$  values as follows. It selects the first node  $v$  in the list randomly and then places the next node  $w$  in the list as the node with the smallest  $rem_{vw}$  value and it keeps doing this until it selects all the nodes in the network. Afterwards, for each session  $s_k$ , the algorithm orders members in the session's TLCs in the list  $\mathcal{X}_{s_k}$  (lines 17-24) as follows. It places the first member in  $\mathcal{X}_{s_k}$  as the first node in the list  $\mathcal{U}$  that is a member in session  $s_k$  and the second member in  $\mathcal{X}_{s_k}$  as the second node in the list  $\mathcal{U}$  that is a member in session  $s_k$  and it keeps doing this until it places all the members. Finally, the algorithm computes the total number of lightpaths needed between each ordered pair of nodes  $(i, j)$  to groom the total traffic  $\sum_{s_k} (N_{s_k} - 1)t_{s_k}$  from all sessions  $s_k \in S_{ji}$  (lines 25-27).

### 5.2.2 Algorithm 2

In this algorithm, a hub node  $h$  is chosen from the set of nodes in the network. The traffic between any two members in a many-to-many session is routed as follows. First, the traffic is routed through a direct lightpath from the first member to the hub and then through a direct lightpath from the hub to the second member. Note that when the hub is the first member then the first step is not needed and when it is the second member then the second step is not needed. According to this algorithm, for each node  $i \neq h$  to receive all its traffic, it needs  $\lceil \sum_{s_k \in S_i} \frac{(N_{s_k} - 1)t_{s_k}}{g} \rceil$  lightpaths incoming from the hub and it needs  $\lceil \sum_{s_k \in S_i} \frac{t_{s_k}}{g} \rceil$  lightpaths outgoing to the hub to send all its traffic. Therefore, the total number of lightpaths  $P$  required

according to this algorithm is given by:

$$\begin{aligned}
P &= \sum_{i=0; i \neq h}^{N-1} \left( \left\lceil \sum_{s_k \in S_i} \frac{(N_{s_k} - 1)t_{s_k}}{g} \right\rceil + \left\lceil \sum_{s_k \in S_i} \frac{t_{s_k}}{g} \right\rceil \right) \\
&\leq \sum_{i=0; i \neq h}^{N-1} \left\lceil \sum_{s_k \in S_i} \frac{(N_{s_k} - 1)t_{s_k}}{g} \right\rceil + \sum_{i=0; i \neq h}^{N-1} \left\lceil \sum_{s_k \in S_i} \frac{(N_{s_k} - 1)t_{s_k}}{g} \right\rceil \\
&= 2L
\end{aligned} \tag{5.8}$$

Therefore, we have the following result:

**Theorem 10.** *Algorithm 2 is a 2-approximation algorithm.*

Note that the optimal way to select the hub node is to select the node  $h$  with the largest  $\left\lceil \sum_{s_k \in S_h} \frac{(N_{s_k} - 1)t_{s_k}}{g} \right\rceil + \left\lceil \sum_{s_k \in S_h} \frac{t_{s_k}}{g} \right\rceil$  value. This minimizes the total number of lightpaths in the network. The full description of this algorithm is shown in Algorithm 2. The algorithm first computes the values of  $I_i$  and  $O_i$  for all the nodes in the network and selects the hub node  $h$  as the node with the largest  $I_i + O_i$  value (lines 3-10). Afterwards, the algorithm computes the total number of lightpaths needed between each node and the hub and between the hub and each node (lines 11-14).

### 5.2.3 Complexity Analysis

Algorithm 1 requires a preprocessing step that constructs the sets  $S_{ij}$ . This step requires visiting all the  $K$  sessions for each pair of nodes  $(i, j)$ , which in total requires  $O(KN^2)$  time. Once these sets are constructed, then the  $rem_{ij}$  values can be computed in  $O(N^2)$  time (lines 3-8). Afterwards, the list  $\mathcal{U}$  is constructed in  $O(N^2)$  time (lines 9-16) and the lists  $\mathcal{X}_{s_k}$  are constructed in  $O(KN)$  time (lines 17-24). Then, Algorithm 1 needs to construct the sets  $S_{jFi}$ . This requires visiting all the members in all the lists  $\mathcal{X}_{s_k}$  for each pair of nodes  $(i, j)$ , which in total requires  $O(KN^3)$  time. Once these sets are constructed, then the  $P_{ij}$  values can be computed in  $O(N^2)$  time (lines 25-27). This drives the time complexity of Algorithm 1 to  $O(KN^3)$ . Algorithm 2, on the other hand, requires a preprocessing step that constructs the sets  $S_i$ . This step requires visiting all the  $K$  sessions for each node  $i$ , which in total requires

```

1 Algorithm 2. Many-to-Many Traffic Grooming: Hub-Based
2  $max = 0$ 
3 for  $i = 0, 1, \dots, N - 1$  do
4    $I_i = \left[ \sum_{s_k \in S_i} \frac{(N_{s_k} - 1)t_{s_k}}{g} \right]$ .
5    $O_i = \left[ \sum_{s_k \in S_i} \frac{t_{s_k}}{g} \right]$ .
6   if  $I_i + O_i > max$  then
7      $h = i$ .
8      $max = I_i + O_i$ .
9   end
10 end
11 for  $i = 0, 1, \dots, N - 1$  ( $i \neq h$ ) do
12    $P_{ih} = O_i$ .
13    $P_{hi} = I_i$ .
14 end

```

$O(KN)$  time. Once these sets are constructed, then the  $I_i$ ,  $O_i$  and  $h$  values can be computed in  $O(N)$  time (lines 3-10). Afterwards, the  $P_{ih}$  and  $P_{hi}$  values are computed in  $O(N)$  time (lines 11-14). This drives the time complexity of Algorithm 2 to  $O(KN)$ .

### 5.3 Other Objectives

Although the main objective of Algorithms 1 and 2 (minimizing the total number of lightpaths established) translates to an overall objective of minimizing the network cost, it is important to evaluate the performance of the two algorithms on other important objectives. In this section, we evaluate the performance of the two algorithms on the number of logical hops traversed by a traffic stream, total amount of electronic switching in the network, and Min-Max objectives.

#### 5.3.1 Number of Logical Hops

The number of logical hops (i.e., lightpaths) traversed by a traffic stream is considered an important performance metric in optical networks since it reflects the number of times the traffic stream undergoes optical-to-electronic ( $O/E$ ) conversion which in turn affects the end-to-end delay. Let  $l_{Alg1}^{s_k, i, j}$  be the number of logical hops traversed by the traffic stream originating

from member  $i \in m_{s_k}$  and destined to member  $j \in m_{s_k}$  according to Algorithm 1. Since such a traffic stream can traverse at most  $N_{s_k} - 1$  lightpaths in the TLCs for  $s_k$  (which have  $N_{s_k}$  lightpaths), then we have the following upper bound:

$$l_{Alg1}^{s_k,ij} \leq N_{s_k} - 1 \quad (5.9)$$

Let  $l_{Alg1}^{s_k,i}$  be the average number of logical hops traversed by a traffic stream originating from member  $i \in m_{s_k}$  according to Algorithm 1. Note that the number of logical hops to the member that immediately follows  $i$  in the TLCs for  $s_k$  is one and to the member after it is two until that last member in the TLCs where the number of logical hops is  $N_{s_k} - 1$ . Therefore,  $l_{Alg1}^{s_k,i}$  can be computed as follows:

$$l_{Alg1}^{s_k,i} = \frac{1 + 2 + \dots + (N_{s_k} - 1)}{N_{s_k} - 1} = \frac{(N_{s_k} - 1)N_{s_k}}{2(N_{s_k} - 1)} = \frac{N_{s_k}}{2} \quad (5.10)$$

Note that the value of  $l_{Alg1}^{s_k,i}$  is the same for all  $i \in m_{s_k}$ . Therefore, the average number of logical hops traversed by a traffic stream in session  $s_k$  according to Algorithm 1 ( $l_{Alg1}^{s_k}$ ) is equal to  $l_{Alg1}^{s_k,i}$  for any  $i \in m_{s_k}$ . Finally, the average number of logical hops traversed by a traffic stream in any of the  $K$  sessions according to Algorithm 1 ( $l_{Alg1}$ ) can be computed as follows:

$$l_{Alg1} = \frac{\sum_{s_k} l_{Alg1}^{s_k}}{K} = \frac{\sum_{s_k} N_{s_k}}{2K} \quad (5.11)$$

Following the same notations for Algorithm 2, we have:

$$l_{Alg2}^{s_k,ij} = \begin{cases} 2, & \text{if } i \neq h \text{ and } j \neq h \\ 1, & \text{otherwise} \end{cases} \quad (5.12)$$

Therefore, we have the following upper bound:

$$l_{Alg2}^{s_k,ij} \leq 2 \quad (5.13)$$

To compute the values of  $l_{Alg2}^{s_k,i}$ , we first consider the case where  $h \in m_{s_k}$  and  $i \neq h$ . In this case, we have:

$$l_{Alg2}^{s_k,i} = \frac{1 \times 1 + (N_{s_k} - 2) \times 2}{N_{s_k} - 1} = \frac{2(N_{s_k} - 1) - 1}{N_{s_k} - 1} = 2 - \frac{1}{N_{s_k} - 1} \quad (5.14)$$

The other two cases is when  $h \notin m_{s_k}$  where we have  $l_{Alg2}^{s_k,i} = 2$  and when  $h \in m_{s_k}$  and  $i = h$  where we have  $l_{Alg2}^{s_k,i} = 1$ . The three cases are summarized as follows.

$$l_{Alg2}^{s_k,i} = \begin{cases} 2, & \text{if } h \notin m_{s_k} \\ 2 - \frac{1}{N_{s_k}-1}, & \text{if } h \in m_{s_k} \text{ and } i \neq h \\ 1, & \text{if } h \in m_{s_k} \text{ and } i = h \end{cases} \quad (5.15)$$

To compute the values of  $l_{Alg2}^{s_k}$ , we have two cases. In the first case where  $h \notin m_{s_k}$ , we have  $l_{Alg2}^{s_k} = 2$ . In the second case where  $h \in m_{s_k}$ , we have:

$$l_{Alg2}^{s_k} = \frac{1 \times 1 + (N_{s_k} - 1) \times (2 - \frac{1}{N_{s_k}-1})}{N_{s_k}} = \frac{2(N_{s_k} - 1)}{N_{s_k}} + \frac{1}{N_{s_k}^2} \quad (5.16)$$

The two cases are summarized as follows.

$$l_{Alg2}^{s_k} = \begin{cases} 2, & \text{if } h \notin m_{s_k} \\ \frac{2(N_{s_k}-1)}{N_{s_k}} + \frac{1}{N_{s_k}^2}, & \text{if } h \in m_{s_k} \end{cases} \quad (5.17)$$

Finally, we have:

$$l_{Alg2} = \frac{\sum_{s_k: h \in m_{s_k}} \left( \frac{2(N_{s_k}-1)}{N_{s_k}} + \frac{1}{N_{s_k}^2} \right) + \sum_{s_k: h \notin m_{s_k}} 2}{K} \quad (5.18)$$

### 5.3.2 Total Amount of Electronic Switching

The amount of electronic switching at a node is equal to the total amount of traffic that this node needs to switch in the electronic domain. This is considered an important cost metric in optical networks since it directly affects the size of the switch at that node. Note that when a node  $i \in m_{s_k}$ , then it will receive  $N_{s_k} - 1$  traffic streams each with  $t_{s_k}$  traffic units from that session. According to Algorithm 1, this node terminates one of the traffic streams, switches  $N_{s_k} - 2$  traffic streams and adds its own traffic stream of  $t_{s_k}$  traffic units (see Fig. 4.2.(a) in Chapter 4). Let  $e_{Alg1}^i$  and  $e_{Alg1}$  denote the total amount of electronic switching at node  $i$  and the total amount of electronic switching in the whole network (at all nodes) according to Algorithm 1, respectively. Then, we have the following:

$$e_{Alg1}^i = \sum_{s_k: i \in m_{s_k}} (N_{s_k} - 2)t_{s_k} \quad (5.19)$$

$$e_{Alg1} = \sum_{i=0}^{N-1} \sum_{s_k: i \in m_{s_k}} (N_{s_k} - 2)t_{s_k} \quad (5.20)$$

To bound the values of  $e_{Alg1}^i$  and  $e_{Alg1}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, node  $i$  has to switch  $Kg(N - 2)$  traffic units. Therefore, we have:

$$e_{Alg1}^i \leq Kg(N - 2) \quad (5.21)$$

$$e_{Alg1} \leq KgN(N - 2) \quad (5.22)$$

According to Algorithm 2, the only node that performs electronic switching is the hub node  $h$ . Note that a traffic that is received at the hub and needs to be delivered to multiple recipients requires the hub to duplicate this traffic and to switch each copy separately. Following the same notations for Algorithm 2, we have the following:

$$e_{Alg2} = e_{Alg2}^h = \sum_{s_k: h \notin m_{s_k}} N_{s_k}(N_{s_k} - 1)t_{s_k} + \sum_{s_k: h \in m_{s_k}} (N_{s_k} - 1)(N_{s_k} - 2)t_{s_k} \quad (5.23)$$

To bound the value of  $e_{Alg2}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, node  $h$  has to switch  $Kg(N - 1)(N - 2)$  traffic units. Hence, we have:

$$e_{Alg2} = e_{Alg2}^h \leq Kg(N - 1)(N - 2) \quad (5.24)$$

### 5.3.3 Min-Max Objectives

In many situations, it is desirable to minimize the maximum of a certain cost metric among all the nodes in the network (e.g., minimizing the maximum number of lightpaths incoming/outgoing at a node or minimizing the maximum amount of electronic switching at a node). Note that if the objective is just to minimize the total number of lightpaths in the network, we may end up with a solution where certain nodes have a large number of lightpaths incoming and outgoing while other nodes have very few. This is generally not desirable since the first kind of nodes may be too expensive or impractical to deploy (47).

First, we consider the maximum number of lightpaths incoming or outgoing at a node according to Algorithms 1 and 2 ( $P_{max}^{Alg1}$  and  $P_{max}^{Alg2}$ , respectively). Due to the use of TLCs in Algorithm 1, the total number of lightpaths incoming to a node is equal to the total number of lightpaths outgoing. Hence, we only focus on the maximum number of lightpaths incoming at a node which can be expressed as follows:

$$P_{max}^{Alg1} = \max_i \left\{ \sum_{j=0; j \neq i}^{N-1} \left\lceil \frac{\sum_{s_k: i F_j} (N_{s_k} - 1) t_{s_k}}{g} \right\rceil \right\} \quad (5.25)$$

To bound  $P_{max}^{Alg1}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, we have the following upper bound:

$$P_{max}^{Alg1} \leq K(N - 1) \quad (5.26)$$

According to Algorithm 2, the hub  $h$  has the maximum number of lightpaths outgoing among all the nodes in the network, and is equal to:

$$P_{max}^{Alg2} = \sum_{i=0; i \neq h}^{N-1} \left\lceil \sum_{s_k: i \in m_{s_k}} \frac{(N_{s_k} - 1) t_{s_k}}{g} \right\rceil \quad (5.27)$$

To bound  $P_{max}^{Alg2}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, we have the following upper bound:

$$P_{max}^{Alg2} \leq K(N - 1)^2 \quad (5.28)$$

Next, we consider the maximum amount of electronic switching at a node according to Algorithms 1 and 2 ( $e_{max}^{Alg1}$  and  $e_{max}^{Alg2}$ , respectively). According to Algorithm 1, the maximum amount of electronic switching at a node can be expressed as follows:

$$e_{max}^{Alg1} = \max_i \left\{ \sum_{s_k: i \in m_{s_k}} (N_{s_k} - 2) t_{s_k} \right\} \quad (5.29)$$

To bound  $e_{max}^{Alg1}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, we have the following upper bound:

$$e_{max}^{Alg1} \leq Kg(N - 2) \quad (5.30)$$

According to Algorithm 2, the hub  $h$  is the only node that performs electronic switching. Hence, we have:

$$e_{max}^{Alg2} = e_{Alg2}^h = \sum_{s_k: h \notin m_{s_k}} N_{s_k}(N_{s_k} - 1)t_{s_k} + \sum_{s_k: h \in m_{s_k}} (N_{s_k} - 1)(N_{s_k} - 2)t_{s_k} \quad (5.31)$$

To bound  $e_{max}^{Alg2}$ , we consider the worst case scenario where each of the  $K$  sessions has  $N$  members each with traffic demand  $g$ . In this case, we have the following upper bound:

$$e_{max}^{Alg2} = e_{Alg2}^h \leq Kg(N - 1)(N - 2) \quad (5.32)$$

## 5.4 Routing and Wavelength Assignment

Once we solve the many-to-many traffic grooming problem and determine the set of lightpaths to be established, we can then consider the routing and wavelength assignment (RWA) problem. In this problem, we need to provision each of the lightpaths on the optical WDM network by determining: 1) the physical route of each lightpath on the optical WDM network, and 2) the wavelength to assign to each lightpath while taking the wavelength continuity constraint into account. The objective is to minimize the total number of wavelengths used  $W$ .

It is to be noted that the RWA becomes completely independent of the fact that we are studying many-to-many traffic once the grooming problem has been solved. In addition to this, the RWA problem has been extensively studied in the literature and it has been proven to be NP-complete. Therefore, we use one of the best existing heuristics for the RWA problem (the LFAP heuristic (46)) which has been shown to use a number of wavelengths that is close to that of a derived lower bound. For a detail description of the LFAP heuristic, the reader is referred to (46).

## 5.5 Numerical Results

In this section, we conduct extensive experiments to evaluate the performance of Algorithms 1 and 2. First, we show that the two algorithms use a number of lightpaths that is significantly close to that of the derived lower bound  $L$ . Second, we compare the performance of the two



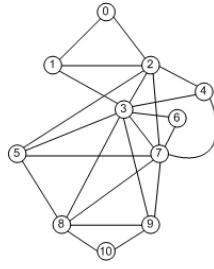


Figure 5.1 The NJ-LATA Network Topology

algorithms on the several objectives mentioned in the paper including the number of lightpaths, number of wavelengths, number of logical hops, amount of electronic switching, and Min-Max objectives.

We consider two sample networks in our experiments. One is the NJ-LATA network (shown in Fig. 5.1) consisting of 11 nodes and 23 bidirectional links and the USNET (shown in Fig. 4.9 in Chapter 4) consisting of 24 nodes and 43 bidirectional links. We randomly generate  $K$  many-to-many session requests as follows. The size of a session is randomly selected between  $[N_{min}, N]$ , while members in a session are randomly selected between  $[0, N - 1]$ . Traffic demand of members in a session is randomly selected between  $[1, 8]$ . We study the performance of each algorithm by varying one of the parameters  $K$ ,  $g$  and  $N_{min}$  at a time. Fig. 5.2.(a) plots the number of lightpaths  $P$  versus the number of sessions  $K$  on NJ-LATA network topology ( $g = 32$  and  $N_{min} = 2$ ), Fig. 5.2.(b) plots the number of lightpaths  $P$  versus the grooming factor  $g$  on NJ-LATA network topology ( $K = 100$  and  $N_{min} = 2$ ), and Fig 5.2.(c) plots the number of lightpaths  $P$  versus the minimum session size  $N_{min}$  on NJ-LATA network topology ( $K = 100$  and  $g = 32$ ). Fig. 5.3.(a) plots the number of lightpaths  $P$  versus the number of sessions  $K$  on USNET network topology ( $g = 32$  and  $N_{min} = 2$ ), Fig. 5.3.(b) plots the number of lightpaths  $P$  versus the grooming factor  $g$  on USNET network topology ( $K = 100$  and  $N_{min} = 2$ ), and Fig 5.3.(c) plots the number of lightpaths  $P$  versus the minimum session size  $N_{min}$  on USNET network topology ( $K = 100$  and  $g = 32$ ).

We can see from the results in Figs. 5.2 and 5.3 that solutions obtained from Algorithms 1 and 2 are significantly close to the derived lower bound  $L$  on a wide range of network parameters  $K$ ,  $g$  and  $N_{min}$ . Since the optimal solution lies between the lower bound and the

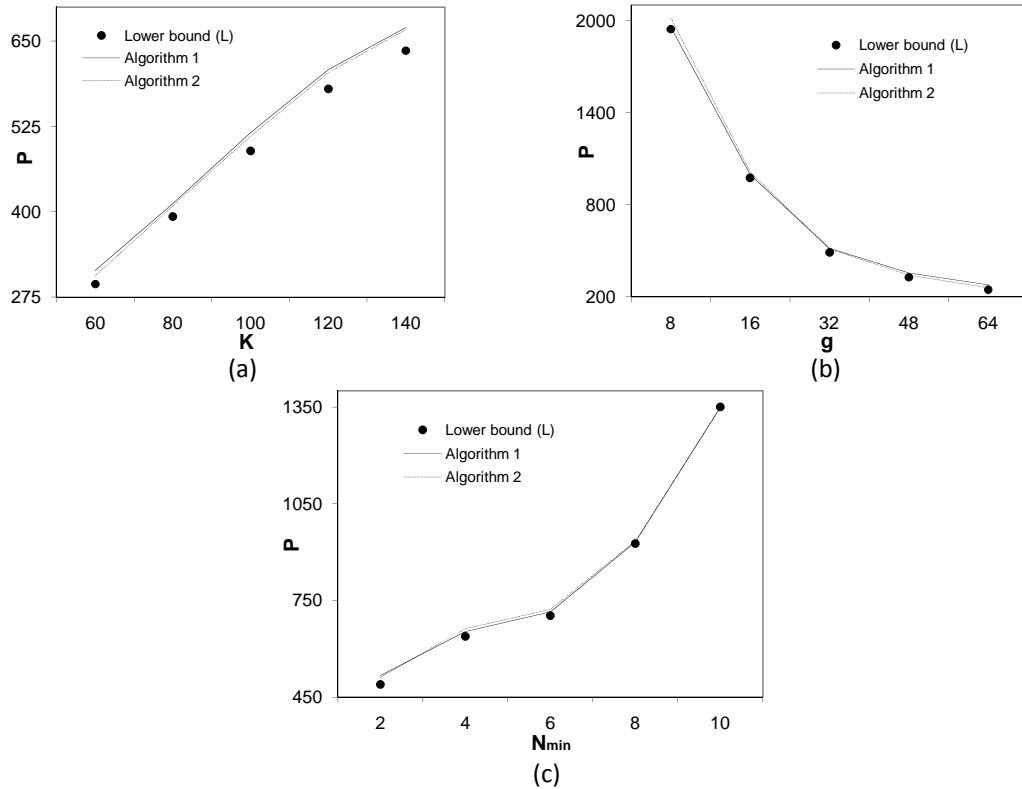


Figure 5.2 Number of lightpaths  $P$  versus (a): number of sessions  $K$ , (b): grooming factor  $g$ , and (c): minimum session size  $N_{min}$  on the NJ-LATA topology

best of Algorithms 1 and 2, we conclude that the two algorithms give near-optimal solutions and that the lower bound  $L$  is tight.

Next, we compare Algorithms 1 and 2 in terms of the number of lightpaths required. Note that the approximation ratio  $1 + \frac{g}{(N_{min}-1)t_{min}}$  of Algorithm 1 becomes better than the 2-approximation ratio of Algorithm 2 when  $(N_{min} - 1)t_{min} > g$ , while it is worst when  $(N_{min} - 1)t_{min} < g$ . Hence, the comparison between the two algorithms is dependent on traffic granularities and on the size of many-to-many sessions.

First, we assume that the size of many-to-many sessions is randomly selected between  $[2, N]$  and we compare the two algorithms by varying traffic granularities of sessions in the network. To make the comparison, we assume a static uniform traffic with all sessions in an experiment having the same traffic demand  $t$  (e.g.,  $t_{s_1} = t_{s_2} = \dots = t_{s_K} = t$ ), where  $1 \leq t \leq g$ . We generate 50 experiments on the USNET each with 100 many-to-many session requests as follows. The

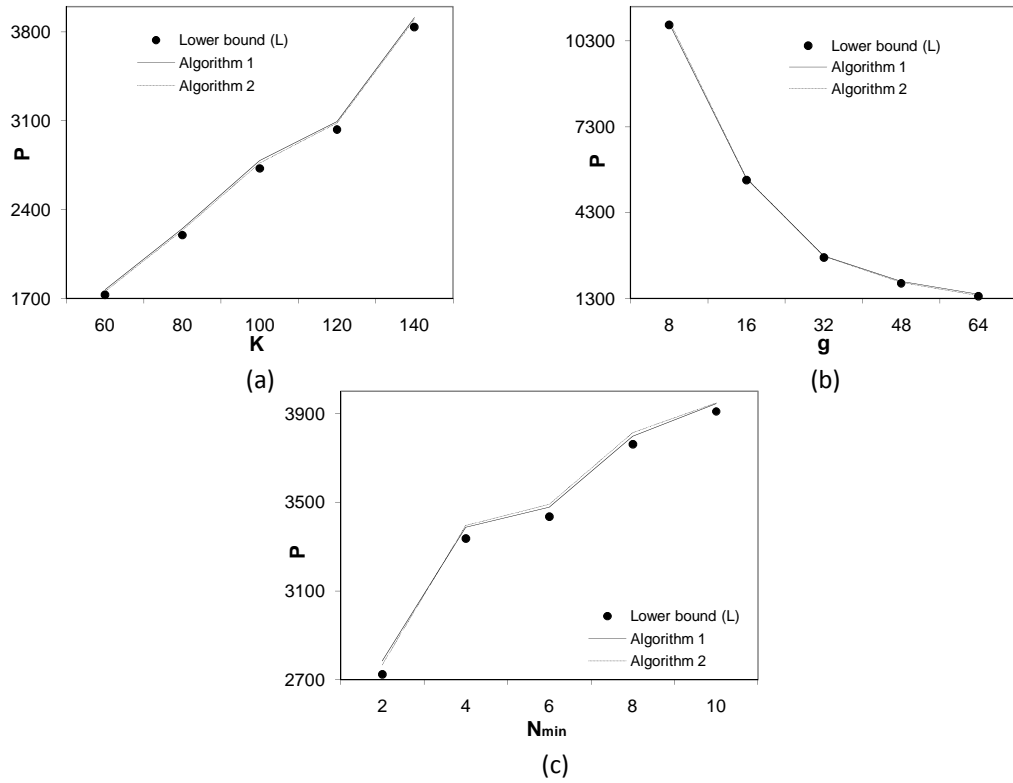


Figure 5.3 Number of lightpaths  $P$  versus (a): number of sessions  $K$ , (b): grooming factor  $g$ , and (c): minimum session size  $N_{min}$  on the USNET topology

size of a session is randomly selected between  $[2,24]$ , while members in a session are randomly selected between  $[0,23]$ . Given the uniform traffic assumption, each of the 50 experiments is conducted for each value of  $t = \{1, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64\}$  ( $g = 64$ ) by each Algorithm. We define the *normalized number of lightpaths* as the ratio of the number of lightpaths  $P$  to the lower bound  $L$  ( $P/L$ ) in an experiment. We also define  $\overline{P/L}$  to be the average value of all  $P/L$  values obtained from the 50 experiments at a particular value of  $t$  by a certain algorithm. The corresponding values of  $\overline{P/L}$  are shown in Fig. 5.4.(a).

Second, we assume that traffic demands of sessions are randomly selected between  $[1,12]$  ( $g = 64$ ) and we compare the two algorithms by varying the minimum session size  $N_{min}$ . At each value of  $N_{min} = \{2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24\}$ , we conduct 50 experiments on the USNET each with 100 many-to-many session requests as follows. The size of a session is randomly selected between  $[N_{min},24]$ , while members in a session are randomly selected

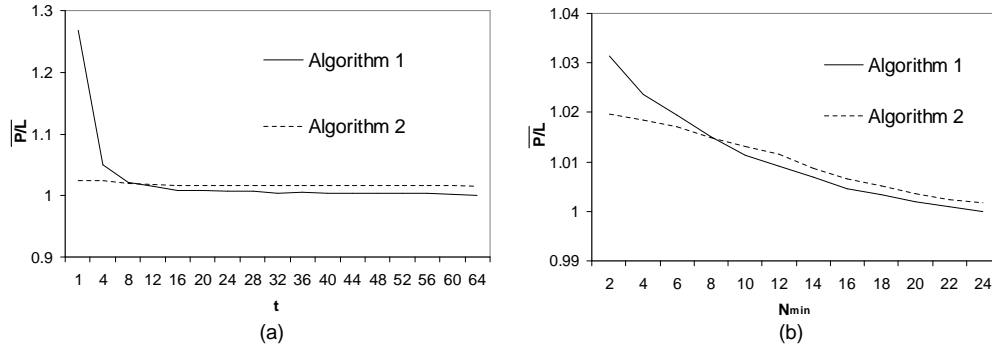


Figure 5.4 (a):  $\overline{P/L}$  versus  $t$  on USNET. (b):  $\overline{P/L}$  versus  $N_{min}$  on USNET

Table 5.2 Comparison between Algorithms 1 and 2 on the objectives  $\bar{l}$ ,  $\bar{e}$ ,  $\overline{P_{max}}$ , and  $\overline{e_{max}}$  on the NJ-LATA

	$\bar{l}$	$\bar{e}$	$\overline{P_{max}}$	$\overline{e_{max}}$
Algorithm 1	3.3	27,205	78	1,730
Algorithm 2	1.34	25,132	991	25,132

between  $[0,23]$ . Traffic demand of members in a session is randomly selected between  $[1,12]$  ( $g = 64$ ). The resulting values of  $\overline{P/L}$ , which is now defined as the average value of all  $P/L$  values obtained from the 50 experiments at a particular value of  $N_{min}$  by a certain algorithm, are shown in Fig. 5.4.(b).

After determining the set of lightpaths for each experiment at each value of  $t$  (or  $N_{min}$ ) by each algorithm, these lightpaths are routed and assigned a wavelength according to the LFAP heuristic (46). We define  $\overline{W}$  to be the average value of all  $W$  values obtained from the 50 experiments at a particular value of  $t$  (or  $N_{min}$ ) by a certain Algorithm. The resulting values of  $\overline{W}$  versus  $t$  and versus  $N_{min}$  are shown in Figs. 5.5.(a) and 5.5.(b), respectively.

Finally, we compare Algorithms 1 and 2 on the other objectives mentioned in the paper. Let  $\bar{l}$ ,  $\bar{e}$ ,  $\overline{P_{max}}$ , and  $\overline{e_{max}}$  denote the average value of the number of logical hops, total amount of electronic switching, maximum number of lightpaths incoming/outgoing at a node, and the maximum amount of electronic switching at a node, respectively for all the 50 experiments conducted above (at the beginning of this section) on a certain network by a certain algorithm. Tables 5.2 and 5.3 show the values of  $\bar{l}$ ,  $\bar{e}$ ,  $\overline{P_{max}}$ , and  $\overline{e_{max}}$  on the NJ-LATA and the USNET networks, respectively using the two algorithms.

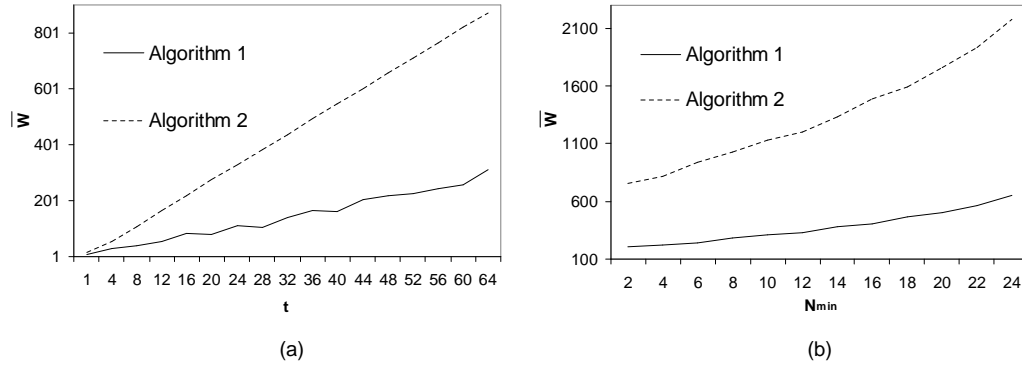


Figure 5.5 (a):  $\bar{W}$  versus  $t$  on USNET. (b):  $\bar{W}$  versus  $N_{min}$  on USNET

Table 5.3 Comparison between Algorithms 1 and 2 on the objectives  $\bar{l}$ ,  $\bar{e}$ ,  $\overline{P_{max}}$ , and  $\overline{e_{max}}$  on the USNET

	$\bar{l}$	$\bar{e}$	$\overline{P_{max}}$	$\overline{e_{max}}$
Algorithm 1	6.8	150,920	173	4,268
Algorithm 2	1.4	145,765	5358	145,765

From Figs. 5.4-5.5 and Tables 5.2-5.3, we draw the following conclusions:

- Algorithm 2 is more cost-effective than Algorithm 1 in packing and grooming low granularity traffic (e.g.,  $t \leq \frac{g}{8}$ ), while Algorithm 1 is more cost-effective when traffic granularities of sessions are relatively high (e.g.,  $t > \frac{g}{8}$ ).
- Algorithm 2 is more cost-effective than Algorithm 1 when the minimum session size is relatively low (e.g.,  $N_{min} \leq \frac{N}{3}$ ), while Algorithm 1 is more cost-effective when the minimum session size is relatively high (e.g.,  $N_{min} > \frac{N}{3}$ ).
- Algorithm 2 consumes much more wavelengths than Algorithm 1. The reason is that all the lightpaths generated by Algorithm 2 are between a certain pair of nodes (nodes and the hub). This results in a large number of lightpaths routed on the same link (hence, using a large number of wavelengths). Algorithm 1, on the other hand, distributes the number of lightpaths among the different pairs of nodes in the network through the use of lightpath cycles. This balances the number of lightpaths to be routed on the same link resulting in a fewer number of wavelengths used.

- As expected, traffic streams in Algorithm 2 use fewer number of logical hops than traffic streams in Algorithm 1, while the total amount of electronic switching by the two algorithms is almost the same. Algorithm 2 performs poorly with Min-Max objectives compared to Algorithm 1. This is also expected since the hub node in Algorithm 2 terminates and originates a large number of lightpaths, while Algorithm 1 distributes and balances the number of lightpaths among the different nodes in the network through the use of lightpath cycles.

## 5.6 Chapter Summary

In this chapter, we derived lower and upper bounds on the number of lightpaths needed to provision a set of many-to-many traffic demands. We also introduced two novel approximation algorithms for the many-to-many traffic grooming problem. Algorithm 1, which is based on lightpath cycles, has an approximation ratio of  $\min\{g, 1 + \frac{g}{(N_{min}-1)t_{min}}, N - N_{min} + 1\}$  while Algorithm 2, which is based on a hub node that collects and distributes traffic, has a 2-approximation ratio. We also evaluated the performance of Algorithms 1 and 2 on three other objectives besides the number of lightpaths, including the number of logical hops traversed by a traffic stream, total amount of electronic switching, and Min-Max objectives. Through extensive experiments, we showed that the two algorithms perform closely to the derived lower bound  $L$ . We also compared Algorithms 1 and 2 on the various objectives mentioned in the paper including the number of wavelengths used.

## CHAPTER 6. DYNAMIC PROVISIONING

### 6.1 Introduction

In Chapters 3, 4, and 5, we dealt with the static many-to-many traffic grooming problem where many-to-many traffic demands are known in advance. Although this is the case in many optical network scenarios, it is possible in other scenarios that the traffic is completely dynamic and that no information about the traffic is known in advance. In these scenarios, it is important to develop efficient online algorithms to provision the dynamic unpredictable traffic. The objective of these algorithms is to minimize the blocking probability of arriving many-to-many sessions. A session will be blocked if, according to the online provisioning algorithm, no sufficient network resources are available to provision it. The main two resources in an optical WDM network are the wavelengths available on each fiber link and the higher layer electronic ports (or *transceivers*) available at each node in the network.

In this chapter, we address the problem of provisioning and grooming of dynamic many-to-many traffic in optical WDM mesh networks. This problem can be stated as follows. Given the current network state represented by the optical WDM network topology and the set of free resources (amount of bandwidth available on existing optical channels, set of free wavelengths on each link, and number of free transceivers at each node in the network). Also, given an arriving many-to-many session request with an arbitrary subwavelength traffic demand (we assume all members in the session have the same traffic demand), determine: 1) The set of new optical channels (lightpaths and light-trees) to establish (if any), 2) How to route and groom the many-to-many session's traffic on the optical channels, and 3) The route and the wavelength to assign to each of the new optical channels (if any) on the optical WDM network. The objective is to provision the session with the minimum number of new resources used

in order to minimize the blocking probability of future sessions. We address the problem in NSTWDM, SHWDM, and SAOWDM networks. In each of the three networks, we propose a number of dynamic provisioning heuristics and provide extensive experiments to evaluate and compare their performance.

The rest of the chapter is organized as follows. In Section 6.2, we formally define the dynamic many-to-many traffic grooming problem and we introduce the assumptions and notations used in the chapter. In Section 6.3, we introduce a number of heuristic algorithms for the dynamic many-to-many traffic grooming problem in NSTWDM networks. In Section 6.4, we introduce heuristic algorithms for the dynamic many-to-many traffic grooming problem in splitting networks (i.e., SHWDM and SAOWDM networks). In Section 6.5, we conduct extensive experiments to evaluate and compare the performance of the proposed heuristics. In Section 6.6, we summarize the chapter.

## 6.2 Problem Description

We define the dynamic many-to-many traffic grooming problem as follows. Given:

1. An arbitrary optical WDM network topology, where the optical nodes either do not support optical splitting (NSTWDM networks) or they fully support optical splitting with unlimited degree of splitting (SHWDM and SAOWDM networks).
2. The current network state represented by the set of optical channels (lightpaths and light-trees) that are currently established, the amount of bandwidth available on each of them, the set of free wavelengths on each fiber link, and the number of free transceivers at each node in the network.
3. An arriving many-to-many session request with an arbitrary subwavelength traffic demand (we assume all members in the session have the same traffic demand).

Provision the many-to-many session on the optical WDM network with the objective of minimizing blocking probability of future many-to-many sessions. In order to minimize the blocking probability of future sessions, the provisioning algorithm must provision the session with the



minimum number of new resources used (bandwidth on existing optical channels, transceivers, and wavelengths). Note that the provisioning of the session may not include the use of any new wavelength or transceiver if we can route and groom the session's traffic on the existing virtual topology without adding new lightpaths or light-trees.

Regarding notation, we use notations that are very similar (with only few differences) to the ones introduced in Table 3.1 in Chapter 3. For completeness, we repeat all the notations here. The optical WDM network has an arbitrary topology represented by an undirected graph  $G(V, E)$ , with a set of nodes  $V$  ( $N = |V|$ ) and a set of physical links  $E$ . Each physical link  $e \in E$  is composed of two unidirectional fibers in opposite directions. The number of wavelengths per fiber is the same among all fibers and is denoted by  $W$ , the grooming factor is denoted by  $g$ , and the number of transceivers available at each node is the same among all nodes and is denoted by  $R$ . An arriving many-to-many session request is denoted by  $s$  with a set of members  $m_s \subseteq V$  with cardinality  $N_s = |m_s|$ . Each member in  $m_s$  has the same traffic demand  $t_s$ , where  $1 \leq t_s \leq g$ . We also define  $H_s = \lceil (N_s - 1)t_s/g \rceil$  to be a lower bound on the number of incoming channels to a member in  $m_s$  in order to receive the traffic from the other  $N_s - 1$  members in the same session. Also, we require that the  $t_s$  traffic units originating from a member and destined to another member in a session  $s$  must not be bifurcated into a set of lower granularity streams each taking a different route on the virtual topology.

### 6.3 Heuristics for NSTWDM Networks

In this section, we introduce heuristic solutions for the dynamic many-to-many traffic grooming problem in NSTWDM networks. In NSTWDM networks, only lightpaths are supported. A direct lightpath (that may span multiple physical links) can be established between any two nodes in the network and it may groom traffic from different sessions and traffic from different members within the same session.

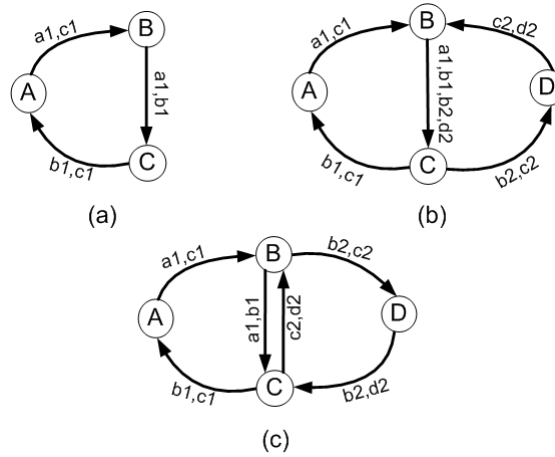


Figure 6.1 (a): LC for a session  $s_1$  where  $m_{s_1} = \{A, B, C\}$  each with one traffic unit denoted as  $a1, b1$  and  $c1$ , respectively ( $g = 4; H_{s_1} = 1$ ). (b): Optimal provisioning of session  $s_2$  (while  $s_1$  in service) where  $m_{s_2} = \{B, C, D\}$  each with one traffic unit denoted as  $b2, c2$  and  $d2$ . (c) Alternative non-optimal provisioning of  $s_2$  (while  $s_1$  in service).

### 6.3.1 Lightpath Cycles Heuristic (LCH)

The basic idea of this heuristic algorithm is to provision arriving many-to-many sessions through transparent lightpath cycles (TLCs), which were introduced in Section 4.1 in Chapter 4. An example of a TLC for a many-to-many session  $s_1$  with a set of members  $m_{s_1} = \{A, B, C\}$  is shown in Fig. 6.1.(a). Note that the TLC for a session  $s$  only describes a virtual topology and it always contains  $N_s$  lightpaths regardless of the order of the members and regardless of the underlying physical topology. In Chapter 4 which dealt with the static many-to-many traffic grooming problem, it was shown that TLCs serve as an optimal virtual topology (in terms of minimizing the total number of transceivers used) to provision a single many-to-many session (see Theorem 3 in Chapter 4).

Although Theorem 3 in Chapter 4 is derived for the static many-to-many traffic grooming problem, it is quite useful in the dynamic version of the problem. For example, consider a network state where there are no sessions in the network and consider an arrival of a many-to-many session  $s$ . Based on Theorem 3 in Chapter 4, the optimal way to provision  $s$  with the minimum number of new resources used is through  $H_s$  TLCs for  $s$ . Here, we focus on

```

1 Algorithm 1. Lightpath Cycles Heuristic (LCH)
   input : An arriving many-to-many session request  $s$  and the current network state
   output: Provisioning of  $s$ 
2 Separate members in  $m_s$  into two disjoint sets  $\mathcal{O}$  and  $\mathcal{N}$ .
3  $order(\mathcal{O})$ .
4  $order(\mathcal{N})$ .
5 for ( $i = 0, 1, \dots, |\mathcal{O}| - 2$ ) do
6   | Provision  $\min\{(N_s - 1)t_s, C_{\mathcal{O}[i], \mathcal{O}[i+1]}\}$  on existing lightpaths between members  $\mathcal{O}[i]$  and
   |  $\mathcal{O}[i + 1]$  in  $VT$ .
7   | Establish  $\lceil ((N_s - 1)t_s - C_{\mathcal{O}[i], \mathcal{O}[i+1]})/g \rceil$  new lightpaths between members  $\mathcal{O}[i]$  and  $\mathcal{O}[i + 1]$ 
   | to provision the remaining unprovisioned traffic (if any).
8 end
9 for ( $i = 0, 1, \dots, |\mathcal{N}| - 2$ ) do
10  | Establish  $H_s$  lightpaths between members  $\mathcal{N}[i]$  and  $\mathcal{N}[i + 1]$ .
11  | if ( $|\mathcal{O}| = 0$ ) then
12  |   | Establish  $H_s$  lightpaths between members  $\mathcal{N}[|\mathcal{N}| - 1]$  and  $\mathcal{N}[0]$ .
13  | end
14  | else
15  |   | if ( $|\mathcal{N}| = 0$ ) then
16  |   |   | Establish  $H_s$  lightpaths between members  $\mathcal{O}[|\mathcal{O}| - 1]$  and  $\mathcal{O}[0]$ .
17  |   | end
18  |   | else
19  |   |   | Establish  $H_s$  lightpaths between members  $\mathcal{O}[|\mathcal{O}| - 1]$  and  $\mathcal{N}[0]$  and  $H_s$  lightpaths
   |   |   | between members  $\mathcal{N}[|\mathcal{N}| - 1]$  and  $\mathcal{O}[0]$ .
20  |   | end
21  | end
22 end

```

the number of new transceivers used since the number of new wavelengths used depends on the routing and wavelength assignment approach used. The way the traffic is routed on the TLCs is as follows. Each member in  $m_s$  transmits its traffic through the  $H_s$  identically ordered TLCs for  $s$  until it reaches the member just before it in the TLCs (see Figure 6.1.(a)). Using this routing strategy, we guarantee two things. First, exactly  $(N_s - 1)t_s$  traffic units are groomed between each pair of consecutive members in the TLCs and therefore  $H_s$  lightpaths are sufficient to groom this traffic. Second, each member in  $m_s$  receives the traffic from the other  $N_s - 1$  members in the same session. Another useful property of the  $H_s$  TLCs is that it equally distributes the use of new transceivers among all the members in the session. This is very important in a dynamic environment where resources (i.e., transceivers) are usually distributed equally among all the nodes in the network.

Although Theorem 3 in Chapter 4 proves the optimality of TLCs in a special case where

```

1 Procedure 1. order( $\mathcal{X}$ )
2 select a member in  $\mathcal{X}$  randomly as the current member.
3 while there is at least one unselected member in  $\mathcal{X}$  do
4   Case 1:  $\mathcal{X} = \mathcal{O}$ 
5     select the next member (from the remaining unselected members) as the member
6     who has the shortest logical distance in  $VT$  from the current member.
7   Case 2:  $\mathcal{X} = \mathcal{N}$ 
8     select the next member (from the remaining unselected members) as the member
9     who has the shortest physical distance in  $G$  from the current member.
10    current member = next member.
11 end

```

there are no sessions in the current network state, many-to-many sessions tend to be provisioned through TLCs even in a network state where there are other sessions that are already provisioned in the network. For example, consider a network state where session  $s_1$  in Fig. 6.1.(a) is still in service and a new many-to-many session request  $s_2$  with a set of members  $m_{s_2} = \{B, C, D\}$  and  $t_{s_2} = 1$  arrives. The optimal provisioning of  $s_2$  in terms of the number of new transceivers used is shown in Fig. 6.1.(b). Note that  $s_2$  is also provisioned through a TLC for  $s_2$  ( $B - C - D - B$ ) and that the TLCs for  $s_1$  and  $s_2$  share the lightpath  $B \rightarrow C$ . More precisely, the lightpath  $B \rightarrow C$  grooms the two traffic units  $a1, b1$  belonging to session  $s_1$  and the two traffic units  $b2, d2$  belonging to session  $s_2$ . Note that the order of the members in the TLC for  $s_2$  is significant. For example, if the order of the members in the TLC for  $s_2$  was  $B - D - C - B$  instead of  $B - C - D - B$ , then the two TLCs for  $s_1$  and  $s_2$  will not share a lightpath and we would require six lightpaths instead of five (see Fig. 6.1.(c)).

In this subsection, we design a heuristic algorithm that assumes that sessions are provisioned through TLCs. More precisely, we assume that each arriving many-to-many session  $s$  is provisioned through TLCs for  $s$  where  $(N_s - 1)t_s$  traffic units are groomed between each pair of consecutive members in the TLCs. Based on this assumption, the heuristic needs to determine two things for each arriving session  $s$ : 1) How to order members in the TLCs for  $s$ , and 2) How to provision the  $(N_s - 1)t_s$  traffic units between each pair of consecutive members in the TLCs. The current virtual topology is represented in the heuristic as a directed graph  $VT$  with a set of nodes that includes every node in  $G$  that at least has one lightpath incoming or outgoing. A directed edge from node  $i$  to node  $j$  exists in  $VT$  only if there exists at least one

lightpath from node  $i$  to node  $j$  in  $G$ . Each edge  $(i, j)$  in  $VT$  has a capacity  $C_{i,j}$  representing the remaining capacity on lightpaths from node  $i$  to node  $j$  in  $G$ .

The heuristic (shown in Algorithm 1) orders members in session  $s$  by first separating the members in  $m_s$  into two disjoint sets  $\mathcal{O}$  and  $\mathcal{N}$ , and then orders each set independently (lines 2-4). The set  $\mathcal{O}$  includes members in  $m_s$  that already exist in the current virtual topology  $VT$ , while the set  $\mathcal{N}$  includes the remaining members in  $m_s$  that do not exist in  $VT$ . The heuristic orders members in the  $\mathcal{O}$  set by minimizing the logical hop distance between each pair of consecutive members, while it orders members in the  $\mathcal{N}$  set by minimizing the physical hop distance between each pair of consecutive members (see Procedure 1). Afterwards, between each pair of consecutive members in the  $\mathcal{O}$  set, the heuristic attempts to provision as much traffic as possible out of the  $(N_s - 1)t_s$  traffic units using existing lightpaths in  $VT$  (lines 5-6). For the remaining unprovisioned traffic (if any), the heuristic establishes  $\lceil ((N_s - 1)t_s - C_{\mathcal{O}[i], \mathcal{O}[i+1]})/g \rceil$  lightpaths between the two members (line 7). Between each pair of consecutive members in the  $\mathcal{N}$  set, the heuristic establishes  $H_s$  lightpaths to provision the  $(N_s - 1)t_s$  traffic units (line 9-10). Finally, the heuristic completes the cycle for each session  $s$  by connecting the  $\mathcal{O}$  set and the  $\mathcal{N}$  set by  $H_s$  lightpaths at both ends (lines 11-21). It is to be noted that all the new established lightpaths in Algorithm 1 (lines 7-21) are routed using shortest path routing and assigned a wavelength according to first fit wavelength assignment.

### 6.3.2 Multicast Heuristic (MH)

Note that a many-to-many session  $s$  with  $N_s$  members can be viewed as a set of  $N_s$  multicast sessions each sourced at one of the members and destined to the remaining  $N_s - 1$  members in the same session. Therefore, one approach to provision a many-to-many session  $s$  is to first break it into  $N_s$  multicast sessions, and then provision each multicast session independently. Multicast traffic grooming has been extensively studied in the literature and many heuristic algorithms have been proposed. A well known heuristic for the dynamic multicast traffic grooming problem is to provision an arriving multicast session on its shortest path tree (SPT). The description of the heuristic is shown in Algorithm 2. The heuristic first breaks the many-

**1 Algorithm 2.** Multicast Heuristic (MH)  
**input :** An arriving many-to-many session request  $s$  and the current network state  
**output:** Provisioning of  $s$   
**2 for** ( $i = 0, 1, \dots, |m_s| - 1$ ) **do**  
**3**     Let  $s_i$  be a multicast session with source  $m_s[i]$  and destinations  $m_s \setminus m_s[i]$ .  
**4**     Construct the shortest path tree for  $s_i$  ( $SPT_i$ ).  
**5**     Provision as much traffic as possible out of the  $t_s$  traffic units from the source  $m_s[i]$  to each of destinations  $m_s \setminus m_s[i]$  on  $SPT_i$  using existing lightpaths.  
**6**     For the remaining unprovisioned traffic (if any), establish new lightpaths on  $SPT_i$  using first fit wavelength assignment.  
**7 end**

to-many session  $s$  into  $N_s$  multicast sessions and then finds the corresponding SPT for each multicast session (lines 2-4). Then, for each multicast session, the heuristic tries to provision as much traffic as possible from the source to each of the destinations on the SPT using existing lightpaths (line 5). Finally, for the remaining unprovisioned traffic (if any), new lightpaths are added on the SPT using first fit wavelength assignment (line 6).

### 6.3.3 Unicast Heuristic (UH)

A many-to-many session  $s$  with  $N_s$  members can also be viewed as a set of  $N_s(N_s - 1)$  unicast sessions each sourced at one of the  $N_s$  members and destined to one of the remaining  $N_s - 1$  members. Therefore, one approach to provision a many-to-many session  $s$  is to first break it into  $N_s(N_s - 1)$  unicast sessions, and then provision each unicast session independently. Unicast traffic grooming has been extensively studied in the literature and many heuristic algorithms have been proposed. A well known heuristic for dynamic unicast traffic grooming is to provision an arriving unicast session on its shortest path (SP) from the source to the destination. The description of the heuristic is shown in Algorithm 3. The heuristic first breaks the many-to-many session  $s$  into  $N_s(N_s - 1)$  unicast sessions and finds the corresponding shortest path for each unicast session (lines 2-5). Then, for each unicast session, the heuristic tries to provision as much traffic as possible on the shortest path using existing lightpaths (line 6). Finally, for the remaining unprovisioned traffic (if any), a new lightpath is added on the shortest path using first fit wavelength assignment (line 7).

```

1 Algorithm 3. Unicast Heuristic (UH)
   input : An arriving many-to-many session request  $s$  and the current network state
   output: Provisioning of  $s$ 
2 for ( $i = 0, 1, \dots, |m_s| - 1$ ) do
3   for ( $j = 0, 1, \dots, |m_s| - 1; j \neq i$ ) do
4     Let  $s_{ij}$  be a unicast session with source  $m_s[i]$  and destination  $m_s[j]$ .
5     Find the shortest path from  $m_s[i]$  to  $m_s[j]$ .
6     Provision as much traffic as possible out of the  $t_s$  traffic units on the shortest path using
       existing lightpaths.
7     For the remaining unprovisioned traffic (if any), establish a new lightpath on the
       shortest path using first fit wavelength assignment.
8   end
9 end

```

## 6.4 Heuristics for Splitting Networks

In splitting networks, lightpaths and light-trees can be used to provision many-to-many sessions. In this section, we introduce heuristic solutions for the dynamic many-to-many traffic grooming problem in splitting networks (SHWDM and SAOWDM networks).

### 6.4.1 Heuristic for SHWDM Networks

In Chapter 4 which dealt with the static many-to-many traffic grooming problem, we have introduced a heuristic algorithm for SHWDM networks that is based on a hub node that collects traffic from members using lightpaths and then distributes the traffic back to the members using light-trees. In this subsection, we extend the heuristic to the dynamic many-to-many traffic grooming problem. More precisely, for each arriving many-to-many session  $s$ , the heuristic selects a hub node from the session's set of members. Each member besides the hub transmits as much traffic as possible out of its  $t_s$  traffic units to the hub on the shortest path using existing lightpaths. For the remaining unprovisioned traffic (if any), a new lightpath is added on the shortest path using first fit wavelength assignment (upstream traffic). Using the new technique of *network coding*, the hub then linearly combines the traffic units received together with its own  $t_s$  traffic units to generate  $N_s - 1$  linearly independent combinations. These combinations must also be linearly independent from each of the original  $t_s$  traffic units received from the members. Afterwards, the  $N_s - 1$  combinations are groomed and delivered

back to the members on the shortest path tree (SPT) from the hub to the members using existing light-trees. For the remaining unprovisioned traffic (if any), new light-trees are added on the SPT using fit wavelength assignment (downstream traffic), see Fig. 1.2 in Chapter 1.

According to this heuristic, each member is guaranteed to recover the original traffic units transmitted by all other members in the same session by linearly combining its own  $t_s$  traffic units with the received combinations (i.e., solving  $N_s$  linearly independent equations). To perform network coding at the hub, we may need to buffer traffic units that arrive early until all traffic units from the  $N_s - 1$  members arrive. As explained in Chapter 1, an MSPP can provide this buffering.

We propose two simple schemes for selecting the hub for an arriving many-to-many session. The first one, most transceivers used (MTU), selects the member with the largest number of used transceivers. The intuition behind this scheme is to select a member with a large number of lightpaths and light-trees originating and terminating. This increases the likelihood of finding existing lightpaths and light-trees to provision the new session's traffic. The second scheme, least transceivers used (LTU), selects the member with the fewest number of used transceivers. The intuition behind this scheme is to distribute the use of transceivers among all the nodes in the network, and not to make certain nodes a bottleneck. The description of the heuristic (which we refer to as the hub-based heuristic (HBH)) is shown in Algorithm 4. The heuristic first selects a hub node for the arriving many-to-many session  $s$  according to MTU or LTU (line 2). Then, for each member in  $s$  besides the hub, the heuristic finds the shortest path to the hub and provisions as much traffic as possible out of the  $t_s$  traffic units using existing lightpaths (lines 3-5). Afterwards, for the remaining unprovisioned traffic (if any), the heuristic establishes a new lightpath on the shortest path using first fit wavelength assignment (line 6). The heuristic then provisions as much traffic as possible out of the  $(N_s - 1)t_s$  traffic units (linear combinations) from the hub  $h$  to the remaining members on the SPT using existing light-trees (line 8). Finally, for the remaining unprovisioned traffic (if any), the heuristic establishes new light-trees on the SPT using first fit wavelength assignment (line 9).

The advantage of network coding in the HBH is the reduction of downstream traffic for



**1 Algorithm 4.** Hub-Based Heuristic (HBH)  
**input** : An arriving many-to-many session request  $s$  and the current network state  
**output**: Provisioning of  $s$

- 2 let  $h$  be the hub node for session  $s$  selected according to MTU or LTU.
- 3 **for** ( $i = 0, 1, \dots, |m_s| - 1; m_s[i] \neq h$ ) **do**
- 4     find the shortest path from  $m_s[i]$  to  $h$ .
- 5     Provision as much traffic as possible out of the  $t_s$  traffic units from member  $m_s[i]$  to hub  $h$  on the shortest path using existing lightpaths.
- 6     For the remaining unprovisioned traffic (if any), establish a new lightpath on the shortest path using first fit wavelength assignment.
- 7 **end**
- 8 Provision as much traffic as possible out of the  $(N_s - 1)t_s$  traffic units (linear combinations) from hub  $h$  to the remaining members on the SPT using existing light-trees.
- 9 For the remaining unprovisioned traffic (if any), establish new light-trees on the SPT using first fit wavelength assignment.

each arriving session  $s$  from  $N_s t_s$  to  $(N_s - 1)t_s$  traffic units. Therefore, the total number of transceivers saved for session  $s$  equals the total number of light-trees saved ( $\lceil N_s t_s / g \rceil - \lceil (N_s - 1)t_s / g \rceil$ ) times the number of transceivers per light-tree ( $N_s$ ), which is given by the following equation:

$$R_{saved}(s) = N_s (\lceil N_s t_s / g \rceil - \lceil (N_s - 1)t_s / g \rceil) \quad (6.1)$$

#### 6.4.2 Heuristic for SAOWDM Networks

In this heuristic, the  $t_s$  traffic units from each member in an arriving many-to-many session  $s$  are delivered directly to the other  $N_s - 1$  members in the same session using a light-tree. For each member, the heuristic attempts to provision as much traffic as possible out of the  $t_s$  traffic units to the other  $N_s - 1$  members using existing light-trees on the shortest path tree (SPT). For the remaining unprovisioned traffic (if any), a new light-tree is added on the SPT. The description of the heuristic (which we refer to as the all-optical heuristic (AOH)) is shown in Algorithm 5. For each member in session  $s$ , the heuristic first finds the SPT to all other members in the same session (lines 2-3). Then, it provisions as much traffic as possible out of the  $t_s$  traffic units on the SPT using existing light-trees (line 4). Finally, for the remaining unprovisioned traffic (if any), the heuristic establishes a new light-tree on the SPT using first fit wavelength assignment (line 5).

According to this heuristic, traffic grooming is only performed when two or more many-to-

**1 Algorithm 5.** All-Optical Heuristic (AOH)  
**input :** An arriving many-to-many session request  $s$  and the current network state  
**output:** Provisioning of  $s$   
**2 for** ( $i = 0, 1, \dots, |m_s| - 1$ ) **do**  
**3**     Construct the shortest path tree from  $m_s[i]$  to  $m_s \setminus m_s[i]$  ( $SPT_i$ ).  
**4**     Provision as much traffic as possible out of the  $t_s$  traffic units from the source  $m_s[i]$  to each of destinations  $m_s \setminus m_s[i]$  on  $SPT_i$  using existing light-trees.  
**5**     For the remaining unprovisioned traffic (if any), establish a new light-tree on  $SPT_i$  using first fit wavelength assignment.  
**6 end**

many sessions with the same member set exist in the network at the same time. Otherwise, no traffic grooming is performed. Therefore, we expect this heuristic to be suitable when traffic demands of user sessions almost fill the capacity of a wavelength channel.

### 6.4.3 Complexity Analysis

The time complexity of the LCH, MH, UH, HBH, and the AOH is dominated by the step of finding the SP/SPT (that has a time complexity of  $O(N^2)$ ) and the step of performing first fit wavelength assignment (that has a time complexity of  $O(W|E|)$ ). These two steps are repeated for each member in the session which drives the time complexity of the LCH, MH, UH, HBH, and the AOH to  $O(N^3 + NW|E|)$ .

## 6.5 Performance Evaluation

In this section, we evaluate and compare the performance of the proposed heuristics for NSTWDM, SHWDM, and SAOWDM networks. We consider two sample networks in our experiments. One is the European Optical Network (EON) shown in Fig. 6.2 and the other is the USNET network shown in Fig. 4.9 in Chapter 4. Many-to-many sessions arrive according to a Poisson distribution with rate  $\lambda$  and they stay in the network for a time that is exponentially distributed with rate  $\mu$ . The capacity of a wavelength channel is OC-48 while the basic unit of traffic is OC-1, and hence the grooming factor is  $g = 48$ . The traffic demand of members in a session is uniformly chosen from the set  $\{OC-1, OC-3, OC-9, OC-12, OC-24, OC-36, OC-48\}$  which represent the recommended rates for OC streams. The number of members in a

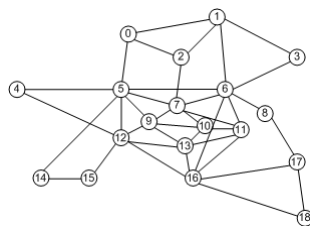
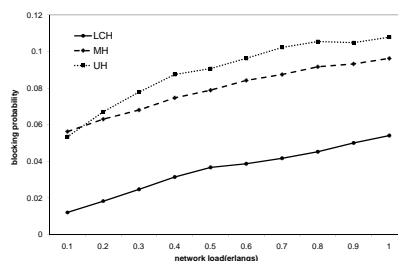


Figure 6.2 EON Network Topology.

Figure 6.3 Blocking probability comparison between LCH, MH and UH in NSTWDM networks on the EON network topology ( $W = 48$  and  $R = 30$ ).

session is uniformly distributed between  $[2, N]$ , while a member in a session is randomly selected between  $[0, N-1]$ . The number of wavelengths per fiber is set to  $W = 48$  in the EON network experiments, while it is set to  $W = 64$  in the USNET network experiments. The number of transceivers at each node is set to  $R = 30$  in the EON network experiments, while it is set to  $R = 40$  in the USNET network experiments. Finally, the number of sessions in each simulation run is set to 1000. Figs. 6.3 and 6.4 show the blocking probability of the three heuristics for NSTWDM networks (LCH, MH and UH) for different values of network traffic load in the EON and the USNET networks, respectively. We can see from the figures that the LCH outperforms both the MH and the UH. This demonstrates the effectiveness of lightpath cycles in provisioning many-to-many sessions. It also demonstrates that a many-to-many session better be viewed as a single session rather than a set of multicast or unicast sessions.

Figs. 6.5 and 6.6 show the blocking probability of the three heuristics for splitting networks (HBH-MTU, HBH-LTU, and AOH) for different values of network traffic load in the EON and the USNET networks, respectively. We can see from the figures that the HBH heuristics, through the novel approach of combining optical splitting and network coding, outperform the

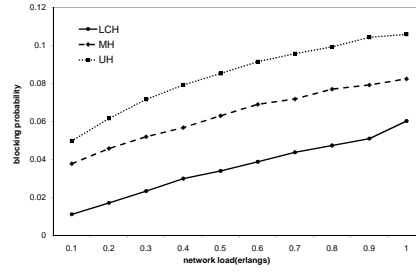


Figure 6.4 Blocking probability comparison between LCH, MH and UH in NSTWDM networks on the USNET network topology ( $W = 64$  and  $R = 40$ ).

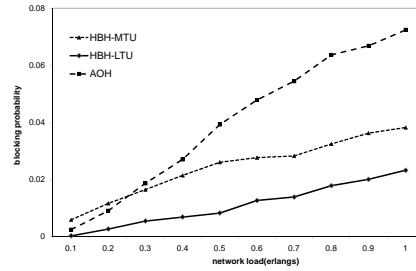


Figure 6.5 Blocking probability comparison between HBH-MTU, HBH-LTU, and AOH in splitting networks on the EON network topology ( $W = 48$  and  $R = 30$ ).

AOH. We can also see from the figures that the HBH-LTU outperforms the HBH-MTU. The intuition behind this is that the HBH-LTU distributes the use of transceivers among all the nodes in the network which avoids making certain nodes a bottleneck. Although the HBH-MTU better utilizes existing lightpaths and light-trees, it makes certain nodes in the network a bottleneck which increases the blocking probability.

Next, we compare the performance of the heuristics for NSTWDM networks with the heuristics for splitting networks. We will show when each of the heuristics is the most suitable choice for dynamic many-to-many traffic grooming. Since the grooming capabilities of the heuristics are varied, their performance will be dependent on traffic granularities of sessions in the network. Therefore, we should compare them for different values of traffic granularities. To make this comparison, we perform eight simulation runs where we fix the traffic demand  $t_s$  of arriving many-to-many sessions in each run to one of the following eight values  $\{OC - 1, OC - 3, OC - 9, OC - 12, OC - 24, OC - 36, OC - 48\}$ , respectively. All other settings of

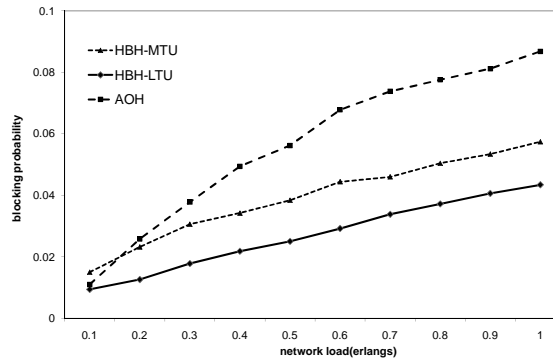


Figure 6.6 Blocking probability comparison between HBH-MTU, HBH-LTU, and AOH in splitting networks on the USNET network topology ( $W = 64$  and  $R = 40$ ).

the eight runs are exactly the same as the settings described earlier at the beginning of this section and the network traffic load of all the runs is fixed to 0.5. Figs. 6.7.(a) and 6.7.(b) compare the blocking probability of the LCH, HBH-LTU and AOH for different values of  $t_s$  on the EON and the USNET networks, respectively.

We can see from Figs. 6.7.(a)-(b) that the heuristic for NSTWDM networks, LCH, is the most suitable choice when traffic granularities of sessions are relatively low (e.g.,  $t_s \leq g/4$ ). This is intuitive since lightpaths are more efficient than light-trees in grooming and packing low granularity traffic. This is a result of the point-to-point nature of a lightpath where it is possible to route many sessions or members with sub-wavelength granularities through it. We can also see from Figs. 6.7.(a)-(b) that the heuristic for SAOWDM networks, AOH, is the most suitable choice when traffic granularities of sessions are relatively high (e.g.,  $t_s \geq 3g/4$ ). This is also intuitive since when traffic granularities of sessions are relatively high, then light-trees are more efficient than lightpaths since a light-tree from a source to a set of destinations requires fewer transceivers than a set of lightpaths each from the source to one of the destinations. Finally, the heuristic for SHWDM networks, HBH-LTU, which uses both lightpaths and light-trees is the most suitable choice when traffic granularities of sessions are in the middle (e.g.,  $g/4 < t_s < 3g/4$ ).

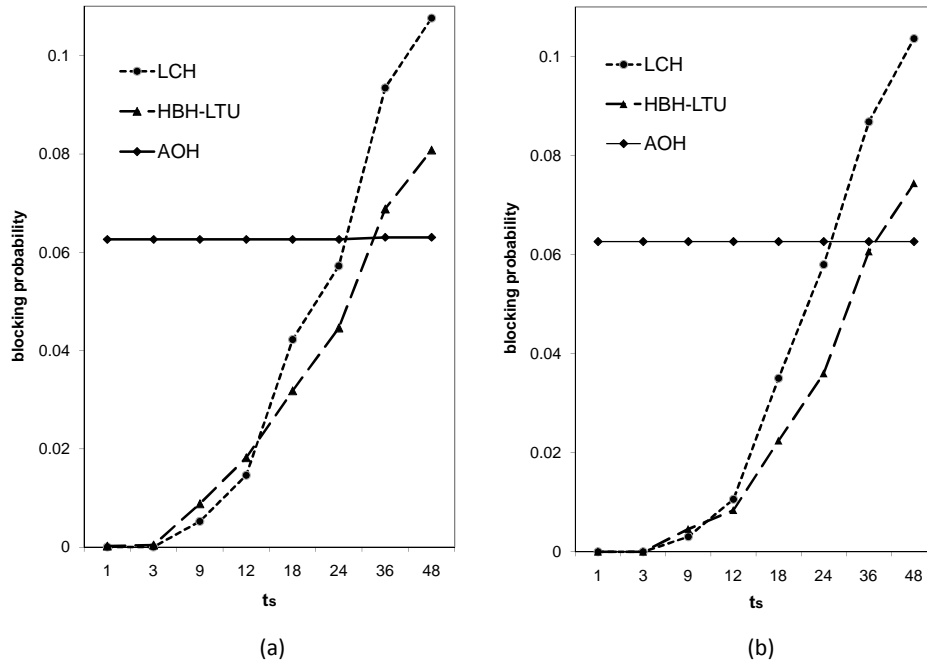


Figure 6.7 (a): Blocking probability comparison between LCH, HBH-LTU and AOH on the EON network ( $W = 48$  and  $R = 30$ ), (b): Blocking probability comparison between LCH, HBH-LTU and AOH on the USNET network ( $W = 64$  and  $R = 40$ ).

## 6.6 Chapter Summary

In this chapter, we have addressed the dynamic many-to-many traffic grooming problem in optical WDM mesh networks. We have introduced different heuristic solutions for the problem in NSTWDM, SHWDM, and SAOWDM networks. It was shown that the LCH, that is based on transparent lightpath cycles, outperforms the multicast and the unicast heuristics (MH and UH, respectively), and that it is the most suitable choice when traffic granularities of sessions are relatively low (e.g.,  $t \leq g/4$ ). It was also shown that the HBH-LTU, through the novel use of network coding, is the most suitable choice when traffic granularities of sessions lie in the middle (e.g.,  $g/4 < t_s < g/4$ ), and that the AOH is the most suitable choice when traffic granularities of sessions are relatively high (e.g.,  $t_s \geq 3g/4$ ).

## CHAPTER 7. SUMMARY AND FUTURE WORK

### 7.1 Summary

In this dissertation, we addressed the many-to-many traffic grooming problem in optical WDM mesh networks. We introduced and analyzed four different network architectures, namely, NSOWDM, NSTWDM, SHWDM, and SAOWDM networks. First, we developed the optimal network provisioning for each of the four networks under static traffic by formulating Mixed Integer Linear Programs (MILPs). Then, we introduced *lightpath cycles* as the optimal virtual topology for a number of special cases in NSOWDM and NSTWDM networks. Based on observations from the optimal solution in NSTWDM and SHWDM networks, we restricted the solution space of the corresponding MILPs to obtain near-optimal solutions in a much shorter time. Also, based on lightpath cycles, efficient near-optimal heuristic algorithms were developed for the many-to-many traffic grooming problem in NSOWDM and NSTWDM networks. In SHWDM networks, we have developed an efficient heuristic algorithm that combines optical splitting and network coding to provision many-to-many sessions. Through extensive experiments, we have shown that solutions from the proposed heuristics are very close to their corresponding optimal solutions.

A major contribution of this dissertation is a comprehensive comparison between the four WDM networks which revealed that each of the WDM networks is the most cost-effective choice (in terms of the costs  $R$  and  $W$ ) for a certain range of traffic granularities. For example, NSOWDM and NSTWDM networks were shown to be the most cost-effective choices when traffic granularities of sessions are relatively low (e.g.,  $t \leq g/4$ ). On the other hand, SAOWDM networks were shown to be the most cost-effective choice when traffic granularities of sessions are relatively high (e.g.,  $t \geq 3g/4$ ). Finally, SHWDM networks were shown to be the most cost-

effective choice when traffic granularities of sessions lie in the middle (e.g.,  $g/4 < t < 3g/4$ ).

Another main contribution of this dissertation is the derivation of lower and upper bounds on the number of transceivers needed and the development of two novel approximation algorithms in the NSTWDM network case. The first algorithm is based on transparent lightpath cycles (TLCs) and has an approximation ratio of  $\min\{g, 1 + \frac{g}{(N_{min}-1)t_{min}}, N-1\}$ , and the second algorithm is based on a hub node that collects and distributes traffic and has a 2-approximation ratio. We also derived bounds and evaluated the performance of the two algorithms on three other important objectives besides the number of transceivers, including the number of logical hops traversed by a traffic stream, total amount of electronic switching in the network, and Min-Max objectives.

A final contribution of this work is the development of online provisioning algorithms for the dynamic many-to-many traffic grooming problem in NSTWDM, SHWDM, and SAOWDM networks. The objective of these provisioning algorithms is to minimize blocking probabilities of arriving many-to-many sessions. The performance of the heuristics proposed in NSTWDM networks demonstrated the effectiveness of lightpath cycles in provisioning many-to-many sessions. It also demonstrated that a many-to-many session better be viewed as a single session rather than a set of multicast or unicast sessions. Finally, similar to the static version of the problem, a comprehensive comparison between the heuristics for NSTWDM, SHWDM and SAOWDM networks revealed that each of the networks is the most suitable choice, in terms of minimizing blocking probability, for a certain range of traffic granularities.

## 7.2 Future Work

We plan to extend the contributions of this dissertation in a number of directions:

- We plan to address the asymmetric many-to-many traffic grooming problem where members within the same session may have different traffic demands. This problem is more challenging than the symmetric one addressed in this dissertation and it makes the analysis more difficult. It is to be noted that the analysis and theorems provided in this dissertation cannot be directly applied to the asymmetric case. However, we believe that



they provide initial, but important insight into the problem and they make the analysis and the derivation of new theorems feasible. Another important challenge in the asymmetric version of the problem is the difficulty of the application of network coding in the SHWDM network since the traffic combined at the hub node from different members within the same session may not have the same granularity. Due to all these new challenges, we believe that the asymmetric many-to-many traffic grooming problem is a new and a different research problem that we plan to address in our future work.

- We plan to address the problem of designing and provisioning of optical WDM networks in the general case where session requests are a mix of unicast, multicast, many-to-one, and many-to-many. Although the problem has been addressed for each of these traffic types separately, the problem of addressing all traffic types together is a new and an interesting research problem. Relying on the solutions proposed for each of these traffic types separately may result in a poor solution for the combined problem. Therefore, developing efficient provisioning strategies that consider all traffic types is an important new research problem.

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