QoS Multicasting and On-Line Traffic Grooming in WDM Optical Networks

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Except where otherwise indicated, this thesis is my own original work.

Arun Vishwanath
23 January 2006
To my parents
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Abstract

Wavelength Division Multiplexing (WDM) optical networks provide enormous bandwidth, and are promising candidates for information transmission in next generation high-speed Internet. In WDM networks, the fiber bandwidth is partitioned into multiple data channels in which different messages can be transmitted simultaneously using different wavelengths. The advances in Wavelength Division Multiplexing and fiber optic technology are seen as the key to satisfying the growing bandwidth demand in the Internet.

As popularity of multicast services such as video conferencing and long distance learning continue to grow, it becomes imperative to design efficient routing and wavelength assignment algorithms to support these services. An important aspect of these real-time multimedia applications is the time dependency. The end-to-end delay Quality of Service (QoS) metric is associated with each source-destination pair and specifies the maximum permissible delay for the data traffic to reach the destination node. Establishing multicast connections with QoS constraints is an important problem in WDM optical networks.

The available bandwidth on a single wavelength in current WDM based optical networks is 10 Gbps and is expected to reach 40 Gbps in the near future. However, the bandwidth requirement of practical applications is only in the sub-wavelength capacity range. Wavelengths are the critical resources in WDM networks. Thus, assigning an entire wavelength to carry only a single sub-wavelength capacity request leads to poor network utilization and undermines the network performance. Traffic grooming is a technique that is used to bridge the huge gap between the available bandwidth on a single wavelength and the user bandwidth requirement. It involves multiplexing several low speed connection requests onto a single high capacity wavelength channel. A practical wide area WDM network architecture for all-optical traffic grooming involves dividing a wavelength into multiple time slots and multiplexing different requests onto different time slots. Such a network is called as a WDM-TDM switched network or a WDM grooming network. It is important to devise new traffic grooming strategies that make better use of the available bandwidth so that the network performance can be maximized.
Motivated by the issues of QoS routing and traffic grooming in WDM optical networks, in this thesis, we first formulate an Integer Linear Program (ILP) to solve the multiple end-to-end delay constrained multicasting problem in a multi-hop WDM optical network. The objective is to minimize the total cost of establishing a set of $k$ multicast sessions in terms of cost of using wavelengths on links and cost of wavelength conversions at intermediate nodes. In bounding the end-to-end delay, we show the need to consider transmission delays on links and wavelength conversion delays incurred at the nodes. We detail the richness of our formulation using the simulation results obtained by solving the ILP on the real-world NSFNET backbone mesh network. We then investigate the on-line traffic grooming problem in WDM grooming mesh networks by developing a novel exponential cost function and an on-line routing algorithm for efficiently grooming sub-wavelength demands in such networks. The cost function not only encourages grooming new sub-wavelength connection requests onto the wavelengths that are being used by existing traffic but also performs load balancing by intelligently increasing the cost of using wavelengths on links. Using experimental results obtained by simulations, we finally evaluate and analyze the performance of the proposed algorithms for both unicast and multicast traffic grooming.
List of Publications

The contents of this thesis have been published in the following journal and conference proceedings.

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Chapter 1

Introduction

1.1 WDM Optical Networks

The explosive growth of the Internet and the advent of World Wide Web services have led to an insatiable demand for high bandwidth capacity at low operating costs. This ever increasing demand is fueled by many factors. The widespread use of the Internet has brought millions of users online, thus leading to a tremendous growth in network traffic. Multimedia services over the Internet such as video-conferencing, distance learning and distributed gaming have gained prominence, and consequently the bandwidth consumption has increased significantly. Modern day businesses continue to rely heavily on high speed communication networks for their day-to-day transactions. All these factors have highlighted the limitations of conventional networking technologies and have motivated network service providers to develop and deploy new technologies.

Wavelength Division Multiplexing (WDM), a key optical networking technology, has emerged as the most promising candidate for meeting this growing bandwidth demand [6, 8, 51, 61]. WDM systems offer unprecedented bandwidth by multiplexing several different wavelength channels into a single optical fiber. Figure 1.1 shows an example of WDM where three independent wavelength channels ($\lambda_1, \lambda_2, \lambda_3$) are multiplexed into the same optical fiber. Information can be transmitted concurrently on these wavelength channels with the bandwidth available on each wavelength being in the order of tens of Gigabits per second.

1.2 Trends in Optical Networking

Optical networks have been instrumental in increasing the bandwidth of communication networks. The trends and the changes in the technology are discussed in this section.
Optical Fiber

\[ \lambda_1 \quad \lambda_2 \quad \lambda_3 \quad \lambda_4 \quad \lambda_5 \]

**Figure 1.1:** Optical fiber carrying 3 different wavelengths

### 1.2.1 First Generation Optical Networks

Optical fiber offers much higher bandwidth than conventional copper cables. In addition, optical fibers are less prone to electromagnetic interferences while maintaining low error rates and low sensitivity to noise [21, 51]. First generation optical networks use optical fiber just as a transmission medium, thus replacing the traditional copper cable. All the processing and switching of data at the intermediate nodes are handled by electronics. Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) are a few examples of first generation optical networks.

### 1.2.2 Second Generation Optical Networks

As research work towards developing novel optical solutions continued, it soon became apparent that optical networks were capable of providing more functions than simple point-to-point communication. With data rates reaching Gbps, processing them quickly using electronics proved to be increasingly difficult. This was one of the key issues that led to the design and development of second generation optical networks. Previously, electronics at any intermediate node had to not only handle all the data that were destined to that node, but also all the data that were being passed through the node onto the other destination nodes in the network. This undermined the performance of the first generation optical networks considerably. Thus, second generation optical networks looked at performing some of the latter routing and switching operations in the optical domain rather than in the electronic domain. As a result, intermediate nodes along the path provide an optical bypass functionality for all the traffic that do not terminate at these nodes. Only traffic terminating at a node is converted from the optical domain into the electronic domain and processed locally at the node. A class of second generation optical network that has gained significant attention in the research community is the *wavelength routing networks* [2, 3, 11, 39, 48, 52, 76].
1.3 Wavelength Routing Network Architecture

A practical network architecture for wide-area WDM networks is one that uses the concept of wavelength routing. A WDM wavelength routing network, shown in Figure 1.2, consists of switching nodes with communication fiber links interconnecting the nodes. The switching nodes are referred to as Optical Cross Connects (OXC). The OXC in the network are capable of routing different wavelengths arriving at an input port to different output ports. Figure 1.3 shows an example of a $3 \times 3$ optical cross connect with two wavelengths per fiber. Wavelengths $\lambda_1$ and $\lambda_2$ arriving at input ports $A$, $B$, and $C$ are first demultiplexed. Each of these independent wavelengths are then sent to an optical switch, which is dedicated to switch signals on each wavelength individually. The outgoing signals from the optical switch are then multiplexed before they are sent out to the respective output ports.

![Figure 1.2: 5 node WDM wavelength routing network](image)

Communication between a source node and a destination node is setup by establishing a lightpath, where a lightpath is defined as an all-optical circuit switched transmission medium that uses the same wavelength along every link in the routing path. A lightpath may traverse several physical fiber links in the optical network. One of the major advantages of wavelength routing networks is that it is transparent to the underlying protocol and bit rates. Once a lightpath is established between a source node and a destination node, the data that is transmitted over this lightpath can use any protocol format. Thus, the optical network acts as an optical layer to support a wide variety of data traffic that are independent of the protocol and bit rates. To illustrate the concept of a lightpath, consider Figure 1.2, in which four lightpaths have been established. The lightpath between nodes 1 and 3, and the lightpath between nodes 5 and 4 are
established on wavelength $\lambda_1$. Since these two lightpaths do not share any common physical fiber link, they can be setup on the same wavelength $\lambda_1$. Now, a lightpath between nodes 5 and 3 shares a common fiber link with the lightpath between nodes 1 and 3. Due to electromagnetic interference, this lightpath must be established on a different wavelength, say $\lambda_2$. This constraint is known as the distinct wavelength constraint. It means that, if two lightpaths share a common fiber link, then they can only be routed on two distinct wavelengths. Note that the lightpaths in the figure all use the same wavelength along every link in the routing path. This constraint is known as the wavelength continuity constraint.

WDM networks can be characterized into two types - single-hop networks [46] and multi-hop networks [47].

- **Single-hop Networks**: Single-hop networks employ a lightpath for transmitting information between a source node and a destination node [85]. In this scenario, the available bandwidth is efficiently utilized since overheads due to wavelength conversion and electronic processing at intermediate nodes are avoided. However, this leads to high blocking probability as the same wavelength has to be used on all the links in the routing path.

- **Multi-hop Networks**: In wide-area WDM networks, the number of wavelengths available in the network is usually limited. In order to utilize the wavelength resources efficiently, and to increase the probability of successfully establishing connection re-
quests\cite{5,50}, multi-hop networks have been proposed. They increase the probability of establishing connection requests by allowing wavelength conversion at the intermediate nodes in the path. Contrary to the lightpath, multi-hop networks employ the concept of a semilightpath, which is obtained by chaining together several lightpaths and allowing wavelength conversion at the intermediate nodes\cite{11}.

### 1.4 Wavelength Conversion

If a network does not have wavelength conversion capabilities, then this constraint precludes a lightpath from using different wavelengths on different physical fiber links. Consider Figure 1.2 where four lightpaths have already been setup. Suppose a new lightpath is to be established between nodes 4 and 2 through node 5. If we assume that the network has only two wavelengths and no wavelength conversion capabilities, then this new lightpath cannot be established. However, if node 5 can perform wavelength conversion, then the new lightpath can be setup using $\lambda_2$ on link 4 – 5 and $\lambda_1$ on link 5 – 2. Such a device that converts the wavelength of a signal arriving at an input port to a different wavelength before it is switched onto an output port is called a wavelength converter\cite{50}. If a device can convert an optical signal from one wavelength to another without the use of electronics, then such a device is referred to as an all-optical wavelength converter. On the other hand, if an optical signal is first converted to the electronic domain and subsequently regenerated on a different wavelength, then such a device is referred to as an opto-electronic wavelength converter. This wavelength conversion technique is also called Optical/Electronic/Optical wavelength conversion or simply O/E/O. Although all-optical wavelength converters have the advantage of being transparent to the protocol format and bit rates, it is well-known that all-optical wavelength converters are prohibitively expensive for commercial use. Opto-electronic wavelength conversion is a mature technology and is thus the preferred choice for performing wavelength conversion. The disadvantage of using this technique is that the protocol transparency no longer exists, and the data is required to maintain a certain format and bit rate.

As explained above, wavelength conversion plays a key role in improving the throughput and the performance of the network. Different types of wavelength conversion exists in a WDM network as shown in Figure 1.4. If an input wavelength can be converted to any other
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output wavelength, then it is called *full wavelength conversion*, Figure 1.4 (a). On the other hand, if an input wavelength can be converted to any of a limited set of output wavelengths, then this is referred to as *limited wavelength conversion*, Figure 1.4 (b). Finally, *fixed wavelength conversion*, Figure 1.4 (c), is a special case of limited wavelength conversion, where an input wavelength can be converted to exactly one other output wavelength.

![Diagram of wavelength conversion types](image)

**Figure 1.4**: Different types of wavelength conversion

1.5 Routing and Wavelength Assignment

A feature unique to WDM optical networks that fundamentally differentiates it from traditional electronic networks is the problem of Routing and Wavelength Assignment (RWA). In WDM networks, a connection request between two end-points is setup using a lightpath, which is implemented by selecting a set of physical fiber links between the source node and the destination node, and reserving a particular wavelength along each of these links. In contrast, the routing path between a source node and a destination node in a traditional electronic network is determined by just a sequence of physical links connecting the two end-points. Therefore, when establishing an optical connection, we must deal with the problem of finding a route as well as allocating an available wavelength along this route. In doing so, we must also take into consideration the two important constraints - the distinct wavelength constraint and the wavelength continuity constraint. This makes the RWA problem significantly more complex than
the routing problem in traditional electronic networks. The RWA problem can be classified into two types - Static RWA and Dynamic RWA. These are briefly described below.

1.5.1 Static RWA

In static RWA, the nature of the traffic pattern is reasonably well-known in advance and variations to the traffic pattern are not expected to happen in short intervals of time. In other words, once a lightpath is established between a source node and a destination node, the lightpath is assumed to be active for relatively long periods of time. Given this scenario, the efficient method for establishing lightpaths between different source-destination pairs is by formulating and solving the static RWA problem. Static RWA is also referred to as off-line RWA since all the traffic demands are completely known in advance. The static RWA problem is usually first formulated as an Integer Linear Program (ILP) to optimize various metrics such as total cost, congestion and number of wavelengths. LP relaxation techniques and various heuristic algorithms can then be employed to find good suboptimal solutions efficiently.

1.5.2 Dynamic RWA

The dynamic RWA problem arises during the real-time operation of the network. Unlike in the static RWA scheme, traffic pattern in the dynamic RWA scheme is not known in advance. Sequence of connection requests arrive and depart from the network in some random fashion. Once a connection request terminates, the resources used by the request are released, and can therefore be used by subsequent incoming requests. The network state at the time of a connection request determines whether or not the request can be established. At any instant of time, the network state consists of physical paths (routes) and the wavelengths that are being used along the paths by various lightpaths that are active at that instant. Thus, for each incoming connection request, a dynamic algorithm must be executed to determine the route and wavelength, if any, on which to establish the request. If such a route and wavelength cannot be found, then the connection request is blocked. The performance of a dynamic algorithm is generally measured using the call blocking probability metric. It is the probability that a new connection request is blocked due to the lack of available resources in the network to establish it. Dynamic RWA algorithms are also referred to as on-line RWA algorithms. Owing to the
real-time nature of the traffic, the dynamic RWA algorithms must be computationally simple.

1.6 The Problems and Related Literature Review

The problems considered in this thesis and the related literature review are described in this section.

1.6.1 QoS Routing and Multicasting

The next-generation multimedia applications such as distributed gaming, medical imaging, video-conferencing and interactive learning demand high throughput and stringent end-to-end delay requirements. This need for timely delivery of information has brought about a new challenge of Quality of Service (QoS) routing. In QoS routing, the aim is to select routes that satisfy the QoS parameters of every connection request, while at the same time ensuring that the resources needed by the connection request are assigned efficiently. A key QoS requirement is the end-to-end delay bound between the source node and the destination node. The objective is not to find a routing scheme that generates a path or a tree with the lowest possible end-to-end delay. However, it is to develop a strategy which ensures that the information arrives at the respective destination nodes within the delay bounds. Consequently, the notion of QoS routing has been proposed to capture the different performance parameters needed by the underlying application [9]. For a unicast connection request, the problem is to find a path between the source node and the destination node such that the sum of the delays along all the links in the path is within the end-to-end delay bound specified by the connection request. For a multicast connection request, the problem is to construct a source-rooted multicast tree such that the total delay along the path in the tree from the source node to every destination node in the multicast group is within than the end-to-end delay bound for that specific source-destination pair. Abundant bandwidth coupled with the advances in optical networking technology gives WDM the potential to satisfy these stringent QoS performance parameters.

1.6.1.1 Related Work

Multicasting is a prominent service that forms an integral part of communication networks already deployed, and is crucial to the communication networks that will be deployed in the
future. It can be viewed as a point-to-multipoint communication between the source node and all the destination nodes in the multicast group. Multicast routing in traditional electronic networks has been widely investigated and several different routing algorithms have been proposed. There is however an essential difference between multicasting in traditional electronic networks and multicasting in WDM networks. Multicasting in the former is focused on constructing a delay bounded multicast tree while minimizing the total cost. Here, only a single cost and delay function is taken into consideration, namely the cost of using a particular link and the communication delay over it [31, 36, 57]. However, in WDM networks, wavelengths constitute an important resource, and hence the cost of wavelength conversion together with the delay incurred due to wavelength conversion at the intermediate nodes are of paramount importance. Therefore, the optimization objective in this case should not only consider the cost of using a wavelength on a link, but also the cost of wavelength conversion at an intermediate node, thereby involving more than one cost metric. Wavelength conversion delay at a node is the delay incurred to convert an incoming wavelength to an outgoing, but different wavelength. Due to speed and other physical limitations of wavelength converters (O/E/O wavelength conversion), wavelength conversion delay plays an important role in bounding the end-to-end delay between source-destination pairs. Hence, this parameter has to be considered in any efficient routing strategy. Thus, while bounding the end-to-end delay, we should not only consider the communication delays on links, but also the delays incurred due to wavelength conversions at the intermediate nodes along the routing path. Also, as wavelengths are the critical network resources, assigning them to communication links efficiently are fundamental to WDM networks. Therefore, the application of traditional multicast routing algorithms to WDM network environment is limited, and warrants the design of efficient Multicast Routing and Wavelength Assignment (MCRWA) strategies.

Multicast routing in WDM networks is an active area of research. The work in [58] addresses the problem of multiple multicasting in WDM networks, its objective is to minimize the network congestion. In [40, 41], the objective is to minimize the cost of establishing one multicast session by considering the cost of wavelength utilization and wavelength conversion. However, these previous works did not deal with constructing multicast trees that bound the end-to-end delay between source-destination pairs. [29] focuses on single-hop networks in an attempt to minimize the number of distinct wavelengths required for constructing a set of QoS
multicast trees at a suboptimal cost, with the assumption that the cost and delay functions are correlated. [22] deals with the problem of minimizing the user blocking probability. It attempts to maximize the system throughput. [28] considers the problem of establishing one multicast session with bounded delays between a source node and a set of destination nodes. However, in their formulation, the cost of wavelength conversion and the wavelength conversion delay are not considered. [85] focuses on establishing a single multicast tree taking into account the cost of wavelength utilization and conversion along with the wavelength conversion delay to bound the end-to-end delay between a source node and a set of destination nodes, however it ignores the communication delays on links.

1.6.2 Traffic Grooming

The vast disparity in the capacity of a single wavelength channel and the bandwidth requirement of a typical connection request has given rise to the concept of traffic grooming [44] in WDM networks. As WDM technology continues to mature, the capacity available on a single wavelength channel is in the order of OC-48/OC-192/OC-768 (2.48Gbps/10Gbps/40Gbps). However, the bandwidth requirement of commercial applications is only in the order of STS-1/OC-1/OC-3. For example, the bandwidth required for High Definition Television (HDTV) is only about 20 Mbps. Clearly, the available bandwidth on a single wavelength far exceeds the capacity requirement of a typical connection request.

In order to utilize the available wavelength capacity efficiently, the concept of traffic grooming has been proposed. Traffic grooming involves multiplexing a number of low-rate independent traffic streams onto a single high capacity wavelength channel. In most present day networks, traffic grooming is realized in the electronic domain, i.e it involves O/E/O at the grooming nodes. The primary advantage of this technique is that once the incoming optical signal is converted into the electronic domain, it can subsequently be regenerated and switched onto the output port on any wavelength. In other words, wavelength conversion can be performed implicitly. However, this advantage comes at the cost of knowing the precise protocol and data format of the incoming traffic at the nodes. It is evident that as the size of the networks continue to increase and more and more networks get deployed, it will be impractical to expect the grooming nodes to understand all the data formats and protocols that could potentially be used in the networks. Doing so will seriously limit the scalability of the networks and un-
1.6 The Problems and Related Literature Review

dermine their performance significantly. All-optical transparent switching functionalities are needed to alleviate the problem.

An all-optical approach to sharing the wavelength capacity among several independent connection requests is to divide a wavelength into multiple time slots and multiplex different requests onto different time slots [64, 66]. Thus, up to \( p \) connection requests can share the same wavelength, assuming each request occupies one time slot and each wavelength is divided into \( p \) time slots. The resulting multiwavelength optical time division multiplexed network is referred to as a WDM-TDM network or a WDM grooming network. Other techniques such as Optical Code Division Multiple Access (OCDMA) and phase modulation can also be employed to share the wavelength capacity. In this thesis, we focus on sharing the wavelength capacity in the time domain and concentrate on WDM-TDM networks.

WDM-TDM networks can be classified into two types - (i) dedicated-wavelength TDM networks and (ii) shared-wavelength TDM networks [75]. In the former, entire wavelengths are dedicated to connection requests between specific source-destination pairs. Connection requests between other source-destination pairs cannot use these dedicated resources and switching is not performed in the time domain at the intermediate nodes along the routing path. In the latter, time slots within a wavelength, rather than the entire wavelength, are dedicated to specific source-destination pairs. Various other connection requests can share the same wavelength on a link by using different time slots for information transmission. The bandwidth available in such networks is used more efficiently than in networks which dedicate entire wavelengths between specific source-destination pairs.

The nodes in a WDM-TDM network have the functionality of multiplexing (demultiplexing) low rate traffic onto (from) a wavelength, and switching them from one lightpath to another, where a lightpath is an all-optical, full-wavelength-capacity transmission medium that uses the same wavelength along the links in the routing path. A WDM-TDM switched network can be viewed as a special case of the shared-wavelength TDM network [63], where all the nodes in the network are capable of grooming traffic and lightpaths to neighboring nodes are established permanently. A connection between a source node and a destination node is setup by assigning time slots on every link in the routing path. Intermediate nodes along the path then switch time slots from one link to the next. Development in optical switching technology has paved the way for fast all-optical switches [14, 32, 34]. All-optical switching
seeks to eliminate electronic switching components and avoids O/E/O conversion. It has other potential benefits such as protocol transparency and bit rate independence, thus overcoming the drawbacks of traditional wavelength routed networks. Use of such all-optical switches in conjunction with fiber delay lines as time slot interchangers have helped realize WDM-TDM switched networks [26, 30].

Wavelength converters convert a signal on one wavelength on to another wavelength. In optical networks without wavelength converters, a signal can only be switched from a certain wavelength at an input port to the same wavelength on an output port. This is the wavelength continuity constraint. Although wavelength converters improve the network blocking performance, all-optical wavelength converters are prohibitively expensive for commercial use. Due to the increasing interest in developing all-optical solutions for traffic grooming, the first generation optical switching technology is expected to obey the wavelength continuity constraint [64, 66], i.e. a connection between two endpoints can be setup on one wavelength only, and wavelength conversion is not allowed at the intermediate nodes along the routing path. Therefore, a node in such a WDM-TDM network can switch time-slots from an incoming wavelength signal at an input port to different time-slots on the outgoing wavelength signal at any output port. The switching, however, is subject to the wavelength continuity constraint.

To illustrate the concept of a WDM-TDM switched network, we use an example (see Figure 1.5), in which each link is assumed to carry two wavelengths and each wavelength is further divided into three time slots. Request $R_1$ originating from node 1 and requiring two time slots
§1.6 The Problems and Related Literature Review

of bandwidth occupies time slots $t_0$ and $t_1$ on link $1 - 3$. Request $R_2$ originating from node 2 and requiring one time slot of bandwidth occupies time slot $t_1$ on link $2 - 3$. In traditional wavelength routed networks, two wavelengths would be required to route these requests on link $3 - 4$ since no two requests can use the same wavelength on the same link. As these requests need only fractional wavelength capacities, allocating full wavelength capacity leads to poor utilization of wavelength resources. However, in WDM-TDM switched networks, only one wavelength would be required, as shown in the figure. Time slots from requests $R_1$ and $R_2$ can be aligned at node 3 before the signal is switched on to link $3 - 4$. An Optical Time Slot Interchanger (OTS) at node 3 delays $R_2$ by one time slot duration so that it can be mapped on to time slot $t_2$ on the resulting outgoing wavelength. It is evident that WDM-TDM switched networks with OTSIs use network resources more efficiently and provides an effective all-optical approach to traffic grooming.

1.6.2.1 Related Work

Previous research on traffic grooming mainly focused on WDM/SONET rings with the objective to minimize the total network cost in terms of the number of SONET add-drop multiplexers [10, 19, 77]. In [15], the authors consider the problem of designing a virtual topology that minimizes electronic routing in an optical ring network. [20] provides network designs for OADM rings that minimize the overall network cost rather than just the number of wavelengths. The authors include the cost of transceivers required at the nodes and the number of wavelengths as metrics for the total network cost.

As WDM networks evolve from rings to arbitrary mesh topologies, addressing the traffic grooming problem in the context of mesh networks is extremely pragmatic. A detailed survey of traffic grooming can be found in [16]. In [78], the authors provide an overview of the architectures for traffic grooming. Static traffic grooming has been widely investigated in the literature [25, 35, 38, 49, 80, 82]. An Integer Linear Program (ILP) formulation can be developed to optimize a certain objective, e.g. network throughput [80], number of transceivers [35], or wavelength usage [38]. [49] presents a Lagrangian-based heuristic for the problem, while [82] investigates the problem using a novel graph model in which different edges can be used to represent various network constraints and different grooming policies can be realized by appropriately manipulating the weights on the edges. In [25], the authors propose a novel all-
optical transport network architecture based on time sliced wavelength channels (WDM-TDM networks) and study static traffic grooming with time slot continuity constraint.

On-line traffic grooming in traditional WDM networks is investigated in [23, 24, 74, 79, 83, 84]. In [79], on-line traffic grooming algorithms are proposed to route connection requests on single/multiple lightpaths, whereas in [74], an agent based mechanism is proposed to achieve higher throughput when grooming traffic at the nodes. In [24], the authors propose a dynamically changing light-tree model using a layered graph to address the problem. In [23], the authors consider the sparse placement of grooming nodes in WDM mesh networks. The connection requests are not uniformly distributed between all node pairs. By appropriately selecting only a subset of grooming nodes, they show that the resulting performance is similar to networks where all the nodes are capable of grooming traffic. In [83, 84], the authors extend their previous work [82] by applying the graph model to solve the on-line traffic grooming problem. Four different grooming policies are presented - (i) Minimize the Number of Traffic Hops on the Virtual Topology (MinTHV), (ii) Minimize the Number of Traffic Hops on the Physical Topology (MinTHP), (iii) Minimize the Number of Lightpaths (MinLP), and (iv) Minimize the Number of Wavelength-Links (MinWL). The experimental results indicate that MinTHV and MinTHP always outperform MinLP and MinWL.

On-line traffic grooming in WDM-TDM switched networks was first investigated in [75]. The work examines the effect of wavelength conversion and time slot interchange on the performance of WDM-TDM networks. Their study concludes that, in networks with small number of wavelengths and large number of time slots per wavelength, significant performance gains can be achieved without the use of wavelength conversion but with the use of time slot interchange alone. In [60], the authors study the effects of wavelength conversion, time slot interchangers and switch reconfigurability on the blocking performance of routing sub-wavelength demands in WDM-TDM networks. The simulation results show that, when connection requests require only a fraction of the wavelength capacity, WDM-TDM routing is much more advantageous than wavelength routing. In [45], the authors investigate a call admission control mechanism to provide fairness control in WDM grooming networks. A Markov Decision Process approach is used to derive an optimal connection admission control policy. In [73], the authors consider on-line traffic grooming in time division multiplexed WDM networks under the assumption that the nodes in the network do not have time slot interchangers. As a result, a connection
request between a source node and a destination node must occupy the same time slot(s) along the links in the path. This can lead to a high blocking probability when compared to networks that incorporate time slot interchange functionality. The problem is solved by first partitioning it into three sub-problems: routing, wavelength assignment and time slot allocation. For every new incoming connection request, each of these sub-problems is then solved separately to determine the route, wavelength and time slot on which to route the request. In [64, 66], the authors consider the general problem of on-line routing in WDM-TDM switched networks with OTSIs, while in [63], they propose a generalized network model called the Trunk Switched Network (TSN) to facilitate modeling and analysis of WDM-TDM switched networks. An analytical model is developed to evaluate the blocking performance of TSNs.

It must be mentioned that in [1], the authors use an exponential cost function and present an on-line routing algorithm for permanent virtual circuits that minimizes the required bandwidth. They show that the algorithm achieves an \( O(\log n) \) competitive ratio with respect to maximum congestion, where \( n \) is the number of nodes in the network. The simulation study in [18] concludes that in traditional electronic networks, routing permanent virtual circuits using exponential cost function leads to improved network performance.

1.6.3 Multicast Traffic Grooming

As popularity of multicast services such as tele-conferencing and distance learning continue to increase, it is imperative for communication networks to support these services efficiently and in a cost-effective manner. It is expected that a large portion of traffic in high-speed networks will be multicast in nature [68]. Multicasting involves the simultaneous transmission of information from a source node to multiple destination nodes. In WDM networks, multicast requests can be efficiently setup using the concept of light-trees [54]. In this approach, individual nodes are equipped with optical splitters that are capable of duplicating an incoming optical signal into two or more identical copies. Provisioning multicast requests using light-trees significantly improves the throughput and the performance of the network. However, as stated previously, connection requests use only a fraction of the total available wavelength capacity. With an increasing interest and demand for multicast communication, it is important to design new multicast traffic grooming algorithms that make effective use of the available wavelength resources so that the throughput, and hence the performance of the network can be maximized.
1.6.3.1 Related Work

Multicast traffic grooming is an area that is just beginning to receive some attention from the research community. As a result, not many studies have been published addressing this important problem. Few recent work that addresses static multicast grooming appear in [5, 7, 13, 42, 68]. In [7], the authors consider multicast traffic grooming in WDM unidirectional ring networks with the objective to minimize the number of Add-Drop Multiplexers (ADMs). Two distinct models of communication are examined, one permitting the same message to be sent on multiple wavelengths and the other restricting each message to be sent exactly once. The authors show that the problem of minimizing the number of ADMs is NP-Complete, and provide good heuristics and approximation algorithms. [42] addresses the multicast traffic grooming problem in WDM ring networks by considering two different node architectures. A heuristic solution to the problem is also presented. In [5], multicast grooming in WDM networks with sparse splitting capabilities is considered. An ILP formulation is provided along with heuristics to minimize the number of wavelengths. [68] presents an ILP formulation along with heuristic algorithms to minimize the network cost in terms of the electronic equipment and the maximum number of wavelengths while [13] gives a non-linear formulation with heuristics to minimize the number of electronic ports.

On-line routing of sub-wavelength multicast requests, however, has received very little attention in the literature. In [65], the authors develop an analytical model for evaluating the blocking performance of tree establishment in WDM-TDM switched optical networks. They extend the TSN model proposed in [63] to the context of multicasting. In [12], a Shortest Path Tree heuristic is presented for grooming multicast traffic in a WDM mesh network whereas in [33], the authors present a hypergraph logical topology design for grooming multicast demands.

1.7 Contributions of the Thesis

In Chapter 2, we consider the end-to-end delay constrained Quality of Service (QoS) multicast routing problem in multi-hop WDM networks. To the best of our knowledge, we are unaware of any previous formulation that aims at realizing multiple, end-to-end delay constrained multicast sessions simultaneously, taking into account (i) the cost of utilizing a wavelength on
§1.7 Contributions of the Thesis

a link, (ii) the cost of wavelength conversion at an intermediate node, (iii) the communication delay on a link, and (iv) the delay incurred due to wavelength conversion at an intermediate node. In this chapter, we first address the above problem and describe the node architecture for a multicast capable wavelength routing switch. We then present an Integer Linear Program (ILP) formulation for efficient MCRWA at a globally optimum cost. An important feature of the formulation is that the cost and delay input metrics are independent of each other. We decouple the cost of utilizing a wavelength on a link from the cost of wavelength conversion at intermediate nodes. Also, the communication delay on a link is decoupled from the delay incurred due to wavelength conversion. Finally, we discuss the experimental results obtained by solving the ILP on the NSFNET backbone mesh network.

In Chapter 3, we first describe the node architecture used for unicast traffic grooming in WDM-TDM switched optical networks. Next, we develop a novel exponential cost function and propose an on-line routing algorithm for traffic grooming in such networks. The algorithm integrates traffic grooming and load balancing with the aim of maximizing the network throughput. It combines path selection and wavelength assignment rather than performing routing and wavelength assignment separately. Using the experimental results obtained by simulation, we study and compare the performance of the proposed algorithm with the other existing algorithms. The results show that the proposed heuristic algorithm outperforms the algorithms discussed and analyzed in [64, 66] for traffic grooming in WDM-TDM switched networks.

In Chapter 4, we consider the on-line multicast routing problem in WDM grooming networks. To the best of our knowledge, ours is the first work to address this important problem. In this chapter, we first propose a node architecture for supporting sub-wavelength demand multicast traffic grooming in WDM grooming networks. We then extend the cost function proposed in Chapter 3 and show how it can be applied to solve the on-line multicast traffic grooming problem. Next, we detail the proposed algorithm with the aim of maximizing the request acceptance of future incoming connections. Finally, we evaluate and analyze the performance of the proposed algorithm with the other well-known multicast tree creation heuristics. The experimental results show that the proposed algorithm outperforms the existing algorithms with respect to various network performance criteria.

We conclude the thesis in Chapter 5 and provide some directions for future work.
Chapter 2

Delay Constrained QoS Multicasting

In this chapter, we consider the problem of establishing multiple multicast sessions in a multi-hop optical wavelength division multiplexing network simultaneously, such that the sum of the cost of realizing these sessions is minimized and at the same time, the end-to-end delay between each source-destination pair is bounded. The cost of a multicast session is expressed in terms of the cost of using a wavelength on a link and the cost of wavelength conversion at a node. The end-to-end delay is bounded by the sum of communication delays on links and wavelength conversion delays at intermediate nodes. We present a solution to the problem by formulating it into an Integer Linear Program (ILP) and solving the ILP on a representative sized mesh network.

The rest of the chapter is organized as follows. In Section 2.1, we introduce the concept of a light-tree that is used to establish multicast communication in WDM optical networks. In Section 2.2 we describe the node architecture capable of performing multicast wavelength routing and wavelength conversion. We formally define the problem in Section 2.3 and present a mathematical Integer Linear Program formulation for the problem in Section 2.4. In Section 2.5, we present the experimental results of our formulation using the NSFNET backbone mesh network. We conclude the chapter in Section 2.6.

2.1 Light-trees

Multicasting in WDM networks can be efficiently setup using the concept of light-trees [54]. Light-trees can be viewed as a point-to-multipoint extension of a lightpath. In this approach, an inherent optical multicasting capability (splitting of light) is introduced in the wavelength routing switches to significantly improve the throughput and hence the performance of the
network. The splitting of light is achieved by employing optical devices known as power splitters in the switches. A power splitter is capable of splitting an optical signal arriving at an input port into two or more identical copies. Each of these identical signals can then be independently switched to different output ports. These switches can also have wavelength conversion functionalities built into them, hence the probability of successfully establishing one or more multicast sessions is increased.

### 2.2 Node Architecture

![Multicast capable wavelength routing switch with wavelength converters](image)

**Figure 2.1:** Multicast capable wavelength routing switch with wavelength converters

An optical WDM network consists of a number of nodes with communication fiber links interconnecting the nodes. Each node in our study is a multicast capable wavelength routing switch with wavelength converters, capable of converting any incoming wavelength to any outgoing wavelength among the wavelengths available in the network, i.e. it has full wavelength conversion functionality. The structure of such a switch is shown in Figure 2.1. For efficient multicasting, the incoming optical signal is split using optical splitters (i.e. replicated into two or more identical copies) for routing [54]. Optical signal $\lambda_1$ on incoming optical fiber $E$ is split
into three identical copies at the node. One copy is dropped locally on wavelength $\lambda_1$ while the other two are routed to outgoing fibers A and E respectively. Wavelength conversion functionalities are useful to such switches as they help reduce the blocking probability of the sessions. As a result, the signal on outgoing fiber A occupies wavelength $\lambda_2$ while the signal on outgoing fiber E occupies wavelength $\lambda_{w-1}$. Observe that the signal $\lambda_i$ from incoming optical fiber A is switched on the same wavelength to the outgoing optical fiber E without any replication. These switches can also perform the local Add/Drop functionalities. As the output signal weakens because of optical splitting, they may have to be amplified before the signal is routed to the respective outgoing fiber links. In the absence of wavelength conversion, the multicast session is known to exhibit the wavelength continuity constraint.

2.3 Problem Definition

We are given a physical topology $G = (V, E)$ representing an optical WDM network along with the set of available wavelengths in the network. The physical topology is both link and node weighted. Each link $(u, v) \in E$ is associated with two weights, one represents the cost of using a wavelength on a link and the other is the communication delay over it. Each node $v \in V$ in the physical topology is a multicast capable wavelength routing switch with full wavelength conversion capabilities as shown in Figure 2.1. As the nodes are capable of performing wavelength conversion, associated with each node are two weights, the cost of wavelength conversion and the wavelength conversion delay respectively.

It is important to detect critical nodes in a network from performing wavelength conversion. For example, it is important to minimize the number of wavelength conversions at the nodes interconnecting two or more important sub-networks or the nodes that monitor the state of the network by running important diagnostics periodically. Thus, the cost of wavelength conversion at these nodes must be much higher than the wavelength conversion costs at the other network nodes. Clearly, the cost of wavelength conversion plays a vital role in minimizing the number of wavelength conversions required to construct a multicast tree.

Wavelength conversion delay is a key parameter that needs to be factored in while bounding the end-to-end delay between any source-destination pair. Optical splitters perform the job of splitting an incoming optical signal into multiple identical copies. The power level of the
optical signals weaken as a result of splitting. Therefore, these signals have to be amplified before they are routed to the respective output ports. Before they are amplified, the incoming wavelength signal has to undergo wavelength conversion using O/E/O techniques. All these factors contribute towards the wavelength conversion delay.

The multiple end-to-end delay constrained multicasting problem is formally defined as follows. Given a set of \( k \) multicast sessions, each consisting of a source node, a number of destination nodes and an end-to-end delay bound between every source-destination pair, our aim is to try and establish all \( k \) multicast sessions using a light-tree based switching architecture such that the total cost of establishing the sessions is minimized and at the same time the end-to-end delay between each source-destination pair of all \( k \) multicast sessions is bounded. The end-to-end delay is the maximum permissible delay along the communication path from the source node to the destination node in the resultant multicast tree.

2.4 Mathematical Formulation

In this section we solve the problem by modeling it as an Integer Linear Program. The following are the notations that will be used in this chapter.

2.4.1 Inputs to the problem

1. A network \( G = (V, E) \) representing a physical topology, consists of \( |V| = n \) nodes and \( |E| = m \) links interconnecting the nodes. Each link in the physical topology is bidirectional and is modeled as a pair of unidirectional links.

2. \( W = \{\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n\} \) is the set of available wavelengths in the network.

3. Every node \( v \in V \) is equipped with a \( d(v) \times d(v) \) multicast capable wavelength routing switch, capable of converting any wavelength \( \lambda' \) on an incoming link \((u, v) \in E\) to any other wavelength \( \lambda'' \) on an outgoing link \((v, t) \in E\) among \( W \) wavelengths. \( d(v) \) denotes the physical degree of node \( v \). This represents the number of incoming (and hence the number of outgoing) physical fiber links at node \( v \).

4. Wavelength utilization cost \( \omega^\lambda_{uv} \), represents the cost of using a wavelength on a physical link between nodes \( u \) and \( v \), where \((u, v) \in E\).
5. Every node $v \in V$ is associated with a cost $C_{v}^{\lambda}$, which represents the cost of converting an incoming wavelength to one or more outgoing wavelengths at node $v$. If an incoming wavelength does not undergo wavelength conversion at node $v$, then $C_{v}^{\lambda} = 0$.

6. $\delta_{u,v}$ denotes the communication delay on a link between nodes $u$ and $v$, where $(u, v) \in E$.

7. $\delta_{v}^{\lambda}$ is the time required to convert an incoming wavelength to an outgoing but different wavelength at node $v \in V$. If an incoming wavelength does not undergo wavelength conversion at node $v$, then $\delta_{v}^{\lambda} = 0$.

8. A set of $k$ multicast sessions to be established. Each multicast session is represented as $S_{i} = \{s_{i}, d_{i1}, d_{i2}, d_{i3}, \ldots \ldots \ldots , d_{ip}\}$. The first element of set $S_{i}$ is the source node $s_{i}$, and the remaining elements of the set are the destination nodes respectively. For $k$ multicast sessions, we have $1 \leq i \leq k$.

9. $\Delta_{i}$ is the end-to-end delay bound between the source node $s_{i}$ and a destination node $d_{ij}$ for session $i$, where $s_{i}, d_{ij} \in S_{i}$.

### 2.4.2 Boolean variables used in the formulation

1. $e_{u,v}^{(\lambda',\lambda)} = 1$, if link between nodes $u$ and $v$ is used by multicast session $i$ on wavelength $\lambda'$, where $(u, v) \in E$, $\lambda' \in W$; otherwise $e_{u,v}^{(\lambda',\lambda)} = 0$.

2. $v_{v}^{i} = 1$, if node $v$ is included in multicast session $i$, i.e. if $v$ is a node in the tree generated for multicast session $i$, where $v \in V$; otherwise $v_{v}^{i} = 0$.

3. $f_{(u,v),d_{ij}}^{(\lambda',\lambda)} = 1$, if one unit of commodity for destination node $d_{ij}$ is used on the link between nodes $u$ and $v$ on wavelength $\lambda'$ for the multicast session $i$, where $(u, v) \in E$, $\lambda' \in W$; otherwise $f_{(u,v),d_{ij}}^{(\lambda',\lambda)} = 0$.

4. $v_{v,(u,v),\lambda'}^{i,d_{ij}} = 1$, if node $v$ is on the path in the tree from the source node $s_{i}$ to the destination node $d_{ij}$ for the multicast session $i$ and performs wavelength conversion from incoming wavelength $\lambda'$ on link $(u, v) \in E$ to any outgoing wavelength $\lambda''$, where $v \in V$, and $\lambda', \lambda'' \in W$; otherwise $v_{v,(u,v),\lambda'}^{i,d_{ij}} = 0$. 


5. \( wc_v^i = 1 \), if node \( v \) performs wavelength conversion for multicast session \( i \), where \( v \in V \); otherwise \( wc_v^i = 0 \).

In our formulation, the wavelength conversion cost is independent of the wavelength conversion delay and vice-versa. In other words, we decouple the cost of wavelength conversion from the wavelength conversion delay. Consider a scenario of a multicast tree where two or more connections from a source node to multiple destination nodes share a few nodes along the path. In this case, all the connections undergo wavelength conversion jointly at the shared node but suffer from wavelength conversion delays individually. Therefore, the wavelength conversion cost must be accounted for only once and in order to verify the end-to-end delay requirement, the wavelength conversion delay must be accounted for separately, i.e., on a per-connection basis. Hence the variables \( wc_v^i \) and \( v_i^{d_j} \) will be associated with the wavelength conversion cost and the wavelength conversion delay respectively.

### 2.4.3 Objective Function

The objective is to minimize the total cost of establishing \( k \) multicast sessions due to wavelength utilization and wavelength conversion.

\[
\text{Minimize} \quad \sum_{i=1}^{k} \sum_{u,v} \sum_{\lambda' = 1}^{\lambda = w} e_{u,v}^{i,\lambda'} \omega_{u,v}^{i,\lambda'} + \sum_{i=1}^{k} \sum_{v=1}^{n} wc_v^i \cdot C_v^i
\]  

(2.1)

The various constraints in the ILP formulation are described next.

### 2.4.4 Constraints

Given a set of \( k \) multicast sessions, the following constraints must be satisfied in order to construct the multicast trees. We classify the various constraints into the following five categories.

- Tree creation constraints
- Integer commodity flow constraints
• Wavelength conversion formulation

• Formulation for the cost of wavelength conversion

• End-to-end delay formulation

1. Tree creation constraints

\[ \forall i, \forall p \in S_i : \quad v^i_p = 1 \quad (2.2) \]

Equation (2.2) ensures that the source node and all the destination nodes of a given multicast session are included in the tree. For example, for session 2, we have \( v^2_{d_1} = 1, v^2_{d_2} = 1, v^2_{d_3} = 1 \); for session 3, we have \( v^3_{d_1} = 1, v^3_{d_2} = 1, v^3_{d_3} = 1, v^3_{d_4} = 1 \), and so on.

\[ \forall i : \quad \sum_{u} \sum_{a,b} c^{i,a,b} = 0 \quad (2.3) \]

As the source node is the root of the multicast tree, it must not have any incoming edges. Equation (2.3) ensures this condition.

\[ \forall i, \forall v \neq s_i : \quad \sum_{u} \sum_{a} c^{i,a,v} = e^i_v \quad (2.4) \]

Equation (2.4) ensures that any node except the source node that belongs to the multicast tree has only one incoming edge. It also ensures that there cannot be any loops in the tree.

\[ \forall i, \forall u \neq d_{ij}, j \geq 1 : \quad \sum_v \sum_{a} c^{i,a,v} \geq e^i_u \quad (2.5) \]

Equation (2.5) ensures that any node that belongs to the tree that is not a destination node has at least one outgoing edge.

\[ \forall i, u : \quad \sum_v \sum_{a} c^{i,a,v} \leq d(u) e^i_u \quad (2.6) \]
The constraint in Equation (2.6) ensures that the number of outgoing edges at a node \( u \in V \) is constrained by the degree of the node, \( d(u) \).

\[
\forall u, v : \sum_i \sum_{\lambda'} e_{u,v}^{i,\lambda'} \leq w
\]  

(2.7)

The constraint in Equation (2.7) restricts the total number of available wavelengths on a link to \( w \). In other words, this constraint ensures that only \( w \) distinct sessions can be routed on a single physical fiber link.

\[
\forall u, v, \lambda' : \sum_i e_{u,v}^{i,\lambda'} \leq 1
\]  

(2.8)

No two sessions sharing the same physical fiber link can have the same wavelength routed on it. This implies that, if any two multicast sessions share a link \((u, v) \in E\), then the wavelength occupied by each of the two sessions on the link \((u, v) \in E\) should be different.\(^1\) This is represented by the constraint in Equation (2.8).

2. Integer commodity flow constraints

\[
\forall i, \forall u = s_i, \forall j \geq 1 : \sum_v \sum_{d_j} \sum_{\lambda'} f_{i(u,v),d_j}^{i,\lambda'} = |S_i| - 1
\]  

(2.9)

For any multicast session \( S_i \), every destination node should receive one unit of commodity. Therefore, the total outflow at the source node \( s_i \) must be equal to the number of destination nodes, \( |S_i| - 1 \). \(|S_i|\) is the cardinality of session \( S_i \) and \( |S_i| - 1 \) is the number of destination nodes respectively. This is represented by Equation (2.9).

\[
\forall i, \forall v = s_i, \forall j \geq 1 : \sum_v \sum_{d_j} \sum_{\lambda'} f_{(u,v),d_j}^{i,\lambda'} = 0
\]  

(2.10)

Equation (2.10) represents the condition that the total inflow to the source node for any multicast session is zero.

\(^1\)Note that link \((u, v) \in E\) is different from link \((v, u) \in E\). Hence, any two distinct sessions can occupy the same wavelength on these two links.
Every destination node in a multicast session must receive one unit of commodity. If a destination node is a relay node, then the total outgoing flow is one less than the total incoming flow since one unit of commodity gets dropped locally at the destination node. Therefore, at any destination node \( d_{ij} \in S_i \), the total incoming flow to \( d_{ij} \) must be equal to one. For all the remaining destination nodes \( d_{iq} \in S_i \) where \( d_{iq} \neq d_{ij} \), the total incoming flow at \( d_{ij} \) must be equal to the total outgoing flow. Observe that if \( d_{ij} \) is a destination node and a leaf node, the total incoming flow is equal to one and the total outgoing flow is zero. At all the remaining nodes \( v \in V \) that belong to the multicast tree that are neither the source node nor the destination nodes, the total incoming flow at \( v \) must be equal to the total outgoing flow. These are represented by the Equations (2.11), (2.12) and (2.13) respectively.

\[
\forall i, u, v : \sum_{d_{ij}} \sum_{\lambda'} \sum_{f(\lambda', d_{ij}, (u,v))}^{j} \leq \left| S_i \right| - 1 \cdot \sum_{\lambda'} \sum_{(u,v)}^{j} \epsilon_{u,v}^{j, \lambda'} \tag{2.14}
\]

\[
\forall i, u, v : \sum_{\lambda'} \sum_{f(u,v, d_{ij})}^{\lambda'} \leq \sum_{d_{ij}} \sum_{\lambda'} \sum_{f(d_{ij}, (u,v))}^{\lambda'} \tag{2.15}
\]

For a given multicast session, the total flow on any link is bounded by the number of destination nodes for that session. Also, if a link is occupied by a session, then there must be some flow on that link, otherwise the flow must be zero. These constraints are represented by the Equations (2.14) and (2.15) respectively.
\[ \forall i, u, v, \lambda ': \sum_{d_{ij}} f_{i(u,v),d_{ij}}^{j'-\lambda'} \leq \left[ |S_i| - 1 \right] e_{u,v}^{j'-\lambda'} \quad (2.16) \]

The total flow on a link for any given multicast session is the number of destination nodes downstream of the link. The flow to all these destination nodes on a link must occupy the same wavelength. Equation (2.16) ensures the same. Observe that this constraint tightly couples the flow and link variables.

3. Wavelength conversion formulation

\[ \forall i, u, v, t, d_{ij}, \forall j \geq 1: \]
\[ v_{i(u,v),\lambda'}, f_{j(u,v),d_{ij}}^{j'-\lambda'} - \sum_{\lambda'' \neq \lambda'} f_{j(u,t),d_{ij}}^{j'-\lambda''} + 1 \geq 0 \quad (2.17) \]

In Equation (2.17), \( v_{i(u,v),\lambda'}^{i.d_{ij}} \) takes the value one if the flow to a destination node \( d_{ij} \) is on wavelength \( \lambda' \) on an incoming link \((u,v) \in E\) at node \( v \) and undergoes wavelength conversion at \( v \) so that the resultant outgoing flow on any link \((v,t) \in E\) occupies a wavelength that is not the same as \( \lambda' \). Note that this variable automatically takes on the value zero if \( v \) is a destination node i.e. if \( v = d_{ij} \).

4. Formulation for the cost of wavelength conversion

\[ \forall i, v: \quad wc_v^j \geq \frac{\sum_{d_{ij}} \sum_{\lambda'} v_{i(u,v),\lambda'}^{i.d_{ij}}}{|S_i| - 1} \quad (2.18) \]

For any multicast session \( S_i \), Equation (2.18) ensures that the cost of wavelength conversion at a node \( v \) is accounted for only once in the objective function. At node \( v \), for a multicast session \( S_i \), the maximum number of wavelength conversions possible is equal to the number of destination nodes for the session \( S_i \), i.e. \( |S_i| - 1 \). As they undergo wavelength conversion jointly, the wavelength conversion cost must be accounted for only once.
5. End-to-end delay formulation

\[
\forall i, \forall j \geq 1, \forall \nu \neq s_i, d_{ij} : \\
\sum_{\nu, u} \sum_{\lambda'} f_{(u, \nu), \lambda'} \cdot \delta_{\nu, \nu} + \\
\sum_{\nu, u} \sum_{\lambda'} v_{i, d_{ij}} \cdot \delta_{\nu}^{\lambda'} \leq \Delta_{ij}
\] (2.19)

Finally, Equation (2.19) represents the formulation for the end-to-end delay bound. A connection from a source node to a destination node can suffer from two delay parameters – communication delay on a link and the delay incurred due to wavelength conversion at the intermediate nodes. Thus, the total end-to-end delay between a source node \(s_i\) and a destination node \(d_{ij}\) for a multicast session \(i\) is the sum of these two delays along its communication path.

2.5 Performance Evaluation

![Figure 2.2: 14 Node NSFNET Backbone Network](image)

To evaluate the effectiveness of our formulation, we conducted experiments by simulation on the NSFNET backbone shown in Figure 2.2. CPLEX [27] is used to solve the ILPs. The numbers along the links in the figure indicate the communication delay over it. The cost of a link is set to a uniform random number \([0, 1]\) times the delay over the link rounded to the nearest integer. Assuming a fixed delay for wavelength conversion at a node, the cost of wavelength conversion at a node is a uniform random number \([0, 1]\) times the delay rounded to the nearest
integer. Our experiments were aimed at analyzing the cost of the multicast sessions as the number of wavelengths in the network, the size of each session and the number of sessions were varied. The size of a session is defined as the number of destination nodes in the session. A multicast session instance comprises of a source node, a set of destination nodes and an end-to-end delay bound between each source-destination pair. As the number of multicast sessions required to be established were varied, 50 session instances were randomly generated and our formulation was executed on each of them. The experiment was performed by setting the size of each multicast session to 3, 6 and 8 nodes or roughly 20%, 40% and 60% of the total network size. The experimental results are shown in Figures 2.3, 2.4, 2.5 and 2.6 respectively.

Figure 2.3 illustrates the plot of the total cost for one multicast session. It can be seen that, as the number of nodes in the session increases, there is a corresponding increase in the total cost as well. For a given session size, it can be observed that increasing the number of available wavelengths in the network does not alter the total cost of the session. To establish one multicast session, only one wavelength is necessary to obtain the optimal solution. Thus, as expected, increasing the number of available wavelengths in the network does not vary the total cost of the generated tree. Therefore, the total cost curves for different wavelengths overlap with each other.

Figure 2.4 is the plot of the total cost for two multicast sessions. With only 1 available wavelength in the network and the size of each session set to 3 nodes (Figure 2.4 (a)), the total cost of the multicast tree varies from 50 to 95 units. However, when the number of available wavelengths is increased to 2, the total cost range is now 50 to 92 units. This slight reduction in the range is natural to expect because of the additional available wavelength resource. The optimizer is free to utilize this additional wavelength for optimal routing so that the total cost is minimized. As the number of available wavelengths is increased beyond 2, further decrease in the total cost is not observed since the number of resources available exceeds the number of resources needed for optimal routing. Similar trend is observed when the size of the session is set to 6 and 8 nodes respectively (Figure 2.4 (b), (c)). In all these cases, the total cost of generating two multicast trees using 2 wavelengths is always less than or equal to the total cost of generating two multicast trees using just 1 wavelength. It can be seen that the total cost of establishing 2 multicast sessions is considerably larger than total cost of establishing 1 multicast session.
§2.5 Performance Evaluation

![Graph](image)

(a) 1 Multicast Session, Size 3 Nodes

![Graph](image)

(b) 1 Multicast Session, Size 6 Nodes

![Graph](image)

(c) 1 Multicast Session, Size 8 Nodes

Figure 2.3: Cost of 1 Multicast session, number of wavelengths varied from 1 to 4
Figure 2.4: Cost of 2 Multicast sessions, number of wavelengths varied from 1 to 4
The next set of graphs in Figure 2.5 show the plot of the total cost for three multicast sessions. With only 1 available wavelength and the size of each multicast session set to 6 nodes, the total cost range is between 143 and 244 units. About 16% of the multicast sessions are not established due to insufficient wavelength resources. This can be seen by the discontinuity in the graph shown in Figure 2.5 (b). When the number of available wavelengths is increased to 2, all the multicast sessions are established successfully. In this case, the total cost range is between 139 and 185 units. Our formulation could successfully exploit the extra available wavelength and thereby globally minimize the total cost of establishing the multicast sessions.

Similar trend is observed with 8 nodes per multicast session (Figure 2.5 (c)). With only 1 available wavelength, the total cost range is between 182 and 242 units. This time however, 40% of the multicast sessions are not setup because of insufficient resources. This is natural to expect because increasing the size of the multicast sessions implies that the number of destination nodes in the sessions increases as well. As a result few more additional links have to be shared across two or more multicast sessions. Since only 1 wavelength is available, the sessions cannot be established because no two sessions can share the same wavelength on the same physical fiber link. This condition is given by Equation (2.8). However, with two wavelengths, all the sessions are established successfully and the total cost ranges between 165 to 220 units. Further reduction in the total cost is not observed when the number of wavelengths is increased beyond 3. The total cost of establishing three multicast sessions is relatively larger than in the previous two scenarios.

We conclude our experiments by establishing 4 multicast sessions as shown in Figure 2.6. With 6 nodes per session and only 1 available wavelength, 82% of the sessions are not established (Figure 2.6 (b)). This can be clearly observed from the discontinuity in the graph. For the few multicast sessions that are established, the total cost ranges between 232 to 284 units. However, with 2 wavelengths, all the sessions are setup and the total cost ranges between 192 to 246 units, a significant reduction in the total cost bounds when compared to the former. This again reflects the richness of our formulation wherein the total cost is minimized globally by successfully exploiting the use of the additional wavelength resources. Finally, with 8 nodes per session and only 1 available wavelength, none of the sessions are setup. However, with the increase in the number of wavelengths, all the multicast sessions are established successfully as shown in Figure 2.6 (c).
Figure 2.5: Cost of 3 Multicast sessions, number of wavelengths varied from 1 to 4
Figure 2.6: Cost of 4 Multicast sessions, number of wavelengths varied from 1 to 4
2.6 Summary

In this chapter, we examined the problem of establishing multiple multicast sessions in a multi-hop optical WDM network simultaneously such that the end-to-end delay between each source-destination pair of all multicast sessions is met rigorously. We solved the problem by formulating it into an ILP so that the total cost of realizing the multicast sessions is minimized. We showed how our formulations can be applied to real world networks and illustrated our results using the representative NSFNET backbone mesh network. From a static design perspective, it might be desirable to run instances with large size for longer time so as to yield optimal solutions. Alternatively, we would be interested in obtaining faster but good sub-optimal solutions. Well-known ILP relaxation techniques can be applied to our formulation to obtain close to optimal solutions and is a subject for future research.
In this chapter, we consider the on-line unicast traffic grooming problem in WDM-TDM switched optical mesh networks without wavelength conversion capability. In such a network, provisioning of connection requests with fractional wavelength capacity requirements is achieved by dividing a wavelength into multiple time slots and multiplexing traffic on the wavelength. We present an on-line traffic grooming algorithm for the concerned problem. The objective is to efficiently route connection requests with fractional wavelength capacity requirements onto high-capacity wavelengths and balance the load on the links in the network at the same time. To do so, we propose a cost function, which not only encourages grooming new connection requests onto the wavelengths that are being used by existing traffic, but also performs load balancing by intelligently increasing the cost of using wavelengths on links. The performance results obtained by experiments on a representative sized mesh network show that the proposed algorithm outperforms the other existing algorithms.

The rest of the chapter is organized as follows. The node architecture and the problem definition are introduced in Section 3.1. The proposed heuristic algorithm is presented in Section 3.2 and the simulation results are discussed and analyzed in Section 3.3. We conclude the chapter in Section 3.4.

3.1 Preliminaries

In this section, we first introduce the node architecture used in our study and then formally define the on-line traffic grooming problem. We then provide a brief overview of the existing algorithms for the concerned problem.
3.1.1 Node Architecture

A WDM-TDM switched mesh network consists of switching nodes and Optical Time Slot Interchangers (OTSIs), with communication fiber links interconnecting these nodes. Each fiber link carries a certain number of wavelengths and each wavelength is further divided into a number of time slots. The node architecture for sub-wavelength demand traffic grooming in such a WDM-TDM switched mesh network is shown in Figure 3.1.

The figure represents a node supporting three links (A, B, C), two wavelengths per link ($\lambda_1, \lambda_2$) and three time slots per wavelength ($t_0, t_1, t_2$). $S_1, S_2, S_3, S_4, S_5,$ and $S_6$ are sessions utilizing 3, 1, 2, 2, 1, and 2 time slots of bandwidth respectively. Session $S_1$ occupying the full bandwidth on $\lambda_1$ is switched from input link A to the same output link. $S_2$ occupying time slot $t_0$ is switched to the same time slot from input link A to output link B on $\lambda_2$. Session $S_3$ arriving on $\lambda_2$ from input fiber link B is dropped locally at the node while session $S_6$ is added at the node and switched to output link B on $\lambda_1$. As there are three time slots per wavelength, the
optical switch can be set in only three possible settings at any given time. When the switch is set to time slots \( t_0 \) and \( t_1 \), the signal \( S_4 \) occupying these time slots on \( \lambda_2 \) is switched from input link \( C \) to output link \( B \). Signals can be delayed using optical time slot interchangers, therefore, time slots on an incoming signal can be mapped on to different time slots on the outgoing signal. Thus, before signal \( S_4 \) is sent on output link \( B \), it undergoes a delay of one time slot duration so that time slots \( t_0 \) and \( t_1 \) on the incoming signal are mapped on to time slots \( t_1 \) and \( t_2 \) on the outgoing signal respectively. When the switch is set to time slot \( t_2 \), \( S_5 \) is switched on \( \lambda_2 \) to the same time slot on the output link \( C \). As wavelength conversion is not incorporated in this architecture, the wavelength of an outgoing signal is the same as its incoming wavelength, thus following the wavelength continuity constraint.

### 3.1.2 Problem Definition

The physical topology of a WDM-TDM switched mesh network is represented by an undirected graph \( G = (V, E) \), consisting of \( |V| = n \) nodes and \( |E| = m \) links interconnecting the nodes. Each link in the physical topology is bidirectional and is modeled as a pair of unidirectional links. \( W = \{\lambda_1, \lambda_2, \ldots, \lambda_w\} \) is the set of available wavelengths in the network. A connection request \( i \) is represented by a quadruple \((s_i, d_i, \beta_i, \Delta_i)\), where \( s_i \in V \) is the source node, \( d_i \in V \) is the destination node, \( \beta_i \) is the required bandwidth and \( \Delta_i \) is the duration of the request.

Given the current network state (routes and wavelengths being used by existing traffic), the on-line unicast traffic grooming problem is to construct a minimum cost bandwidth guaranteed path \( P_i^\lambda \) on wavelength \( \lambda \in W \) that connects the source node \( s_i \) to the destination node \( d_i \). The aim is to maximize the network throughput. We assume that the established requests cannot be interrupted. The connection requests arrive one after the other and the arrival sequence is not known in advance.

### 3.1.3 Routing Algorithms

Traffic grooming in WDM-TDM switched networks can be classified into two types - static and dynamic. In static traffic grooming, all source-destination pairs and their associated bandwidth requirements are known in advance. On the other hand, in dynamic traffic grooming, also
known as on-line traffic grooming, connection requests with varying bandwidth requirements arrive one at a time in some random fashion. Efficient on-line routing and wavelength assignment algorithms will be needed to determine the routing path and the corresponding wavelength on which to establish these requests. Based on the information used for establishing a path between the source node and the destination node [67], on-line routing algorithms can be classified into two types, (i) destination-specific routing algorithms and (ii) request-specific routing algorithms. Destination-specific routing algorithms try to establish the best possible routing path between the source node and the destination node without any knowledge of the incoming connection request. In other words, they establish routing paths without taking into account the bandwidth requirement of connection requests. An example is the shortest path routing based on just minimizing the hop count between the source node and the destination node. These routing algorithms are suited for networks where all the connection requests have similar characteristics. On the other hand, request-specific routing algorithms aim to establish the best possible routing path between the two endpoints taking into account the bandwidth requirement of the incoming connection request. This technique is well suited for networks where the request characteristics vary significantly.

In [64, 66], the authors propose and study a new request-specific routing algorithm called Available Shortest Path (ASP) and compare its performance with two other destination-specific routing algorithms - Widest Shortest Path (WSP) and Shortest Widest Path (SWP). Their results indicate the importance of using request-specific routing algorithms for improving the performance of WDM-TDM switched networks. ASP outperforms the two destination-specific routing algorithms not just in terms of blocking probability but also with respect to other metrics such as fairness and utilization. We give a brief overview of these algorithms below. It must be noted that, since wavelength conversion is not allowed, the routing algorithms are iteratively executed for each \( \lambda \in W \) to determine the best possible path and wavelength on which to route the request.

(i) **Widest Shortest Path (WSP).** Dijkstra's algorithm is used to find the widest path between the source node and the destination node. If two or more paths are the same with respect to this metric, the path with the minimum hop count is selected. If two paths have the same hop count, then the tie is broken by choosing the path corresponding to the first-fit wavelength assignment policy.
(ii) Shortest Widest Path (SWP). This is similar to the conventional shortest path routing based on the hop count. If the hop count of two or more paths are the same, then the widest one among them is chosen. In case of a tie, the path corresponding to the first-fit wavelength assignment policy is selected.

(iii) Available Shortest Path (ASP). In this approach, only links with sufficient bandwidth capacity to accommodate the request are considered for route computation. Dijkstra’s algorithm is then used to determine the shortest path between the source node and the destination node. If two or more paths can accommodate the request, then the path with the minimum hop count is chosen. If there is a tie, then the tie is broken by using the first-fit wavelength assignment policy.

To illustrate how heuristic ASP works, we consider the example shown in Figure 3.2, which represents a five node subnet - 0, 1, 2, 3, 4, of a large mesh network. Assume that the current network configuration of this subnet is as follows. One wavelength \( \lambda_0 \) is available on links 0 – 1 and 1 – 2, and two wavelengths \( \lambda_0, \lambda_1 \) are available on links 0 – 4, 4 – 3 and 3 – 2 respectively. We further assume that the total capacity available on a wavelength is 1, with sessions requiring fractional wavelength capacities. The order of sessions arriving are: \( S_1: 0 \rightarrow 2, S_2: 0 \rightarrow 2 \) and \( S_3: 1 \rightarrow 2 \). Each session requests bandwidth equivalent to half of the wavelength capacity. The values within the parenthesis along the links in the figure indicate the wavelength and the amount of bandwidth used by the sessions.

\( S_1 \) is routed along the links 0 – 1 – 2 as shown in Figure 3.2 (a) on \( \lambda_0 \). To facilitate full-
duplex communication, the bandwidth requested by sessions is reserved along the links in either direction. Thus, following the establishment of $S_1$, $S_2$ is also routed along the links $0\rightarrow 1\rightarrow 2$ on $\lambda_0$. As a result, node 1 is *logically disconnected* from the network along with the links $0\rightarrow 1$ and $1\rightarrow 2$, since no further wavelengths are available on these links while $S_1$ and $S_2$ continue to remain active. By logical disconnection we mean, the links incident to a node *cannot* be used by future connection requests as they do not have any more wavelengths available. In provisioning high speed connections, traffic requests are expected to have long holding times [20]. Thus, logical disconnection of nodes result in fewer routing paths for each subsequent connection request, increasing the number of blocked requests and in turn leading to significant loss of revenue. Consequently, the new session $S_3$ is blocked due to the lack of available wavelengths to route it.

### 3.2 On-Line Traffic Grooming Algorithm

In this section, we first give an overview of the proposed algorithm. Next, we present a connection admission policy and introduce the cost function used in the proposed algorithm. Then, we describe how the cost function realizes traffic grooming and load balancing interests simultaneously. We finally detail the proposed algorithm.

#### 3.2.1 Overview of the proposed algorithm

We propose a routing scheme, On-line Traffic Grooming Algorithm (OTGA), which (i) encourages grooming new sub-wavelength connection requests onto the wavelengths that are being used by existing traffic, and (ii) incorporates load balancing functionality simultaneously. To do so, we introduce a cost function that takes into consideration the *total load on a link* and the *residual available bandwidth on each wavelength*. For every new incoming connection request, Dijkstra's algorithm is used to establish the routing path between the source node and the destination node. As each connection request can only be routed on a single wavelength, at most $w$ shortest paths can be generated, where $w$ is the total number of wavelengths available in the network. Out of all the resulting wavelengths that can be used to establish the request, the wavelength corresponding to the least cost routing path is selected. Here, the cost of establishing the request is the sum of the cost of all the wavelength-links in the routing path. If two paths have the same cost, then the first-fit wavelength assignment policy is employed to break
§3.2 On-Line Traffic Grooming Algorithm

the tie. The bandwidth required by the connection request is then reserved along the links in
the path. In the following, we use an example (see Figure 3.2(b)) to explain the idea behind
the proposed algorithm.

As in the ASP scheme, $S_1$ is routed along the links $0 - 1 - 2$ as shown in Figure 3.2 (b)
on $\lambda_0$. This increases the load on the links $0 - 1$ and $1 - 2$. Since links $0 - 4$, $4 - 3$, and $3 - 2$
have more wavelengths, it is desirable to use these links to route future connection requests
and prevent the depletion of wavelengths on links $0 - 1$ and $1 - 2$. Therefore, higher costs are
assigned to $\lambda_0$ on links $0 - 1$ and $1 - 2$ for subsequent connection requests. As a result, $S_2$
is routed on $\lambda_0$ along the shortest path $0 - 4 - 3 - 2$. Now $S_3$ can be successfully established on
$\lambda_0$ along the direct link $1 - 2$. Therefore, unlike in the Available Shortest Path routing strategy,$S_3$ is not blocked in the proposed routing scheme. Note that if links $0 - 1$ and $1 - 2$ had two
wavelengths instead of one, then it might be desirable to groom connection $S_2$ along with the
already established connection $S_1$.

3.2.2 Connection Admission Policy

We define distance as the minimum number of hops needed by any routing algorithm to route a
connection request between the source node and the destination node. In other words, distance
is the number of hops in the shortest path between the two endpoints in $G = (V, E)$ without
considering the availability of wavelengths on links. The shortest path between nodes 0 and
2 in the mesh network (Figure 3.2) consists of only 2 hops. Therefore, the distance between
nodes 0 and 2 is 2. The number of hops used by OTGA to establish connection request $S_2$
between nodes 0 and 2 is 3 (see Figure 3.2 (b)). From these two hop counts we note that,
in some cases, the number of hops needed by OTGA, and hence the amount of wavelength
resources used by it is greater than the corresponding resources needed by the ASP routing
scheme.

To minimize the utilization of additional wavelength resources, we introduce the following
connection admission policy. Let $D_i$ be the distance (computed a priori) between the nodes
$s_i$ and $d_i$, and $\epsilon$ be the additional number of hops OTGA can take to establish the connection
request between the nodes $s_i$ and $d_i$. This implies that, even if sufficient bandwidth is available
on a wavelength $\lambda \in W$ to route request $i$, the request is blocked if the total number of hops
in the resulting routing path is greater than $(D_i + \epsilon)$. Note that $\epsilon$ is independent of the two
endpoints of the connection request and the associated bandwidth requirement. Instead, it is an experimental parameter that is tuned depending on the physical topology of the network.

3.2.3 Cost Function

The cost function used in the algorithm is described below.

We denote $\Omega$ as the total available bandwidth per wavelength. Let $\mu_{u,v}$ represent the total available bandwidth on a link between nodes $u$ and $v$. Therefore, we have

$$\forall (u,v) \in E : \quad \mu_{u,v} = w \times \Omega.$$  \hspace{1cm} (3.1)

For convenience, we normalize the requested bandwidth to the total available bandwidth on a link. Therefore,

$$\hat{\beta}_i(u,v) = \frac{\beta_i}{\mu_{u,v}}.$$  \hspace{1cm} (3.2)

Let $\mathcal{P} = \{P_1,P_2,P_3,\ldots,P_k\}$ be the set of routing paths assigned to connection requests 1 through $k$. If a request $j$ is rejected, or terminates before the arrival of a new request, then $P_j = \emptyset$, where $P_j$ is the routing path for request $j$ ($1 \leq j \leq k$). Therefore, the load on link $(u,v) \in E$ after considering request $k$ is defined as

$$I_{k,u,v}^j = \sum_{j=1}^{k} \hat{\beta}_j(u,v).$$  \hspace{1cm} (3.3)

In WDM-TDM switched networks, bandwidth requirements of connection requests are expressed in terms of the number of time slots. In this work, we assume that each wavelength is sub-divided into 16 time slots and the capacity of each time slot is equivalent to 1 OC-3 channel. Therefore, the total capacity of each wavelength is equivalent to 1 OC-48 channel, and we have $\Omega = 16$ OC-3s.

Let $\tau_{\lambda_j}(u,v)$ be the number of OC-3 channels being used on link $(u,v)$ by request $j$ on wavelength $\lambda_j \in W$. Then, after considering request $k$, the total number of $\lambda_j$ OC-3 channels being used on link $(u,v)$ is
On-Line Traffic Grooming Algorithm

³.2

(3.2)

\[ U_{u,v}^{k,\lambda'} = \sum_{j=1}^{k} \tau_{j,\lambda'}(u,v). \tag{3.4} \]

\[(u,v) \in P_j \]

When a new connection request \( i \) arrives, we assign costs to each wavelength \( \lambda' \in W \) on the links in \( E \) as follows.

(i) If the capacity of \( \lambda' \) available on link \( (u,v) \) is equal to \( \Omega \), i.e. \( \lambda' \) is not being used by any existing connection request, then the cost of using \( \lambda' \) on it is

\[ \Psi_{u,v}^{\lambda'} = a \left( \frac{\beta_i(u,v)}{a} - 1 \right). \tag{3.5} \]

(ii) Otherwise, \( \lambda' \) is currently being used by existing traffic, and two cases arise.

Case 1. If the residual capacity of \( \lambda' \) on link \( (u,v) \) is less than \( \Omega \), but no less than the requested bandwidth \( \beta_i \), then the cost of using \( \lambda' \) on it is

\[ \Psi_{u,v}^{\lambda'} = \frac{a}{b} \left( \frac{R_{\lambda'}^{i}(u,v)}{a} - 1 \right), \tag{3.6} \]

where \( a \) and \( b \) are appropriately chosen constants. Here, \( R_{\lambda'}^{i}(u,v) \) is the residual capacity of \( \lambda' \) on link \( (u,v) \) after considering the first \( k \) requests, and is given by

\[ R_{\lambda'}^{i}(u,v) = 1 - \frac{U_{u,v}^{k,\lambda'}}{\Omega}. \tag{3.7} \]

Importantly, observe that, to realize load balancing and grooming interests, the constants \( a \) and \( b \) in the cost function must be greater than 1.

Case 2. If the residual capacity of \( \lambda' \) on link \( (u,v) \) is less than \( \beta_i \), then \( \Psi_{u,v}^{\lambda'} = \infty \), which means it cannot be used to establish the routing path.

Note that, from Equation (3.5), if \( \lambda' \) is not being used by any existing connection request on link \( (u,v) \) (i.e. full wavelength capacity of \( \lambda' \) is available on link \( (u,v) \)), then the cost assigned to it represents the change in its relative load that would occur if it were to be used.
by the new connection request [1]. From Equation (3.6), if the residual capacity of \( \lambda' \) on link \((u, v)\) is less than \( \Omega \), but no less than the requested bandwidth \( \beta_i \), then the cost of \( \lambda' \) on this link is expressed as a function of the change in its relative load and the residual capacity of \( \lambda' \). In other words, load balancing is realized by increasing the cost of using wavelengths on heavily loaded links, thus discouraging them from being used by new connection requests.

To encourage grooming new connection requests onto the wavelengths that are already being used by existing traffic, the costs of these wavelengths are further decreased by a factor of their residual capacities. Therefore, among the wavelengths that are currently being used on a link, we encourage grooming on the wavelength that has the highest residual capacity. This minimizes the logical disconnection of nodes from the network and achieves our objective.

### 3.2.4 Algorithm

We are now ready to introduce the detailed algorithm as follows. Once a new connection request arrives, the algorithm is executed to determine whether the request is accepted.

**Algorithm OTGA\((s_i, d_i, \beta_i, D_i, E)\)**

begin

\[ C_{\text{MAX}} \leftarrow \infty; \lambda \leftarrow \text{nil}; P_i^\lambda \leftarrow \text{nil} \]

/* \( C_{\text{MAX}} \) is the total cost to establish request \( i \), \( \lambda \) is the resulting wavelength on which */

/* to route request \( i \), \( P_i^\lambda \) is the routing path for request \( i \), \( \Omega \) is the total capacity per */

/* wavelength, Num_Hops \((P_i^\lambda)\) returns the number of hops in \( P_i^\lambda \) */

**Step 1.** Tear down and free the wavelength resources used by all the connection requests that terminate before the arrival of connection request \( i \).

\[ \forall (u, v) \in E : \hat{\beta}_i(u, v) \leftarrow \frac{\beta_i}{\hat{\mu}_{u,v}} \]

**Step 2.** for each wavelength \( \lambda' \in W \) do

**Step 3.** Compute \( RC\,(u, v, \lambda') \), the residual capacity of \( \lambda' \) on link \((u, v)\) \( \in E \)

**Step 4.** if \( RC\,(u, v, \lambda') = \Omega \) then \( \Psi^{\lambda'}_{u,v} \leftarrow \text{cost from Equation (3.5)} \)

else if \( \beta_i \leq RC\,(u, v, \lambda') < \Omega \)

then \( \Psi^{\lambda'}_{u,v} \leftarrow \text{cost from Equation (3.6)} \)

else \( \Psi^{\lambda'}_{u,v} \leftarrow \infty \)

endif;

endif;
Step 5. Using Dijkstra's algorithm, find a shortest path $P_{(\lambda', i)}$ from $s_i$ to $d_i$ w.r.t costs $\Psi^L_{\lambda', i}$. Let $c_i$ be the sum of the cost of all the links in $P_{(\lambda', i)}$.

Step 6. if $c_i < C_{\text{MAX}}$ then

$$C_{\text{MAX}} \leftarrow c_i; \lambda \leftarrow \lambda' ; P^\lambda_i \leftarrow P_{(\lambda', i)}$$

endif;

endfor;

Step 7. if $C_{\text{MAX}} \neq \infty$ then

if Num\_Hops($P^\lambda_i$) $\leq (D_i + \varepsilon)$ then

for each link $(u, v) \in P^\lambda_i$ do

$$RC(u, v, \lambda) \leftarrow RC(u, v, \lambda) - \beta_i$$
$$RC(v, u, \lambda) \leftarrow RC(v, u, \lambda) - \beta_i$$

endfor;

return path $P^\lambda_i$;

endif;

endif;

Step 8. return "request blocked"

e end.

The computational complexity of the proposed algorithm can be analyzed as follows. The shortest path from the source node to the destination node can be found using Dijkstra's algorithm, which can be implemented in $O(m + n \log n)$ time using Fibonacci heaps. Therefore, the time complexity of the algorithm is $O(w(m + n \log n))$ as it is run once for each $\lambda' \in W$ with $w = |W|$.

### 3.3 Simulation Study

In this section, we first introduce the simulation environment and then present the experimental results. We analyze the performance of OTGA using various network performance metrics and compare the results with the other existing algorithms.
3.3.1 Simulation Environment

To evaluate the performance of the proposed algorithm, we conducted experiments on a representative sized mesh network shown in Figure 3.3, which consists of 24 nodes and 43 fiber links. Each fiber link carries 16 wavelengths. All the nodes in the network have the architecture shown in Figure 3.1. We further assume that the wavelength continuity constraint is imposed.

![Figure 3.3: A 24 node telecom network](image)

The bandwidth required by connection requests is uniformly distributed between 1 OC-3 and 16 OC-3s. The request arrival is a Poisson process with the traffic uniformly distributed between all node pairs. The connection holding time is exponentially distributed. The load (in Erlangs) on the network is varied by increasing the average connection holding time. We simulate 200,000 connection requests to obtain the network performance under a certain network load. The simulations were performed on a Linux PC with a 2.8 GHz Pentium IV processor and 512 MB of memory. The average running time to simulate 200,000 connection requests is about 20 minutes. In all our experiments, the constants $a$, $b$ and $c$ are fixed at 4, 2 and 2 respectively. We also experimented with other set of values and found the above combination to give consistently good network performance across all loads.

3.3.2 Experimental Results

We compared the performance of OTGA with the other existing algorithms - WSP, SWP and ASP. The metrics used to measure the performance of the algorithms are (i) bandwidth blocking
ratio, (ii) network utilization, (iii) average capacity of accepted requests (fairness) and (iv) normalized revenue.

![Bandwidth Blocking Ratio](image)

**Figure 3.4:** Bandwidth blocking ratio versus load in Erlangs

(i) **Bandwidth blocking ratio.** Figure 3.4 compares the bandwidth blocking ratio of different routing algorithms. It represents the percentage of the amount of blocked traffic over the total amount of bandwidth required by all the connection requests during the entire simulation period. It can be observed from the figure that, at low network loads (in Erlangs), the percentage of bandwidth blocked by OTGA and ASP is similar. This is because, at low loads, the average connection holding time is less. The costs assigned to all the links derived from the cost function are nearly identical. Therefore, the performance of OTGA and ASP are similar.

With the increase in the average connection holding time, the network load also increases. The exponential nature of the cost functions in Equations (3.5) and (3.6) prevent the depletion of wavelengths on heavily loaded links by assigning to it, costs, that are significantly higher than the costs assigned to lightly loaded links. This in turn leads to the creation of routing paths that are distributed among the links evenly. From the figure it can be seen that, as the network load increases, the bandwidth blocking ratio increases as well. However, the percentage of total bandwidth blocked by OTGA is lower than that of the other three heuristics. OTGA delivers
higher network throughput, and thus offers better performance.

(ii) **Average network utilization.** The average network utilization is determined as follows. Consider a connection request \( i \) between nodes \( s_i \) and \( d_i \) with the capacity requirement \( \beta_i \). Let the distance between them be \( D_i \). Now, if connection request \( i \) is to be established, then irrespective of the routing algorithm used, the minimum capacity required in the network is \( \beta_i \times D_i \). This is called the *effective capacity requirement* of the request. Depending on the routing algorithm employed, the number of hops taken by it to establish the connection request may be greater than \( D_i \).

Denote by \( ENC \), the effective network capacity utilized at any instant of time. \( ENC \) is defined as the sum of the effective capacity requirement of all the connection requests that are active at that instant. The total network capacity is defined as \( m \times |W| \times \Omega \). The network utilization is then determined as the ratio of the effective network capacity utilized to the total network capacity as \( \frac{ENC}{m \times |W| \times \Omega} \). We compute the network utilization at intervals of every 250 incoming requests, and average it over 200,000 connection requests. The resulting curves are plotted in Figure 3.5.

![Figure 3.5: Average network utilization by different routing algorithms](image)

WSP achieves the least network utilization because it routes connection requests over
longer paths. This results in over usage of wavelength resources. The connection admission policy introduced in OTGA leads to effective utilization of bandwidth, thereby achieving the maximum network utilization.

(iii) Average capacity of accepted requests. Figure 3.6 shows the average capacity of accepted connection requests in terms of the number of OC-3 channels. With the increase in the network load, routing algorithms exhibit a bias in favor of connection requests that require smaller capacities. Larger capacity requests experience higher blocking than requests requiring smaller capacities.

An ideal routing algorithm will have a constant value for this metric at all network loads. Since the bandwidth requirement is uniformly distributed between 1 OC-3 and 16 OC-3s, an ideal routing algorithm in our simulation environment will establish an equal number of connection requests requiring 1 OC-3, 2 OC-3s, 3 OC-3s, \ldots, 16 OC-3s of bandwidth. That is, the average capacity of connection requests accepted by an ideal routing algorithm will be 8.5 OC-3s. A routing algorithm demonstrates better fairness over another one if it has a higher value with respect to this metric. The closer this value is to 8.5 OC-3s, the better is its performance. Figure 3.6 compares the average capacity of accepted connection requests.
It can be seen that OTGA realizes more higher capacity requests than the other three routing algorithms. This shows that OTGA provides improved fairness and reduces the bias in favor of establishing connection requests requiring smaller capacities.

![Figure 3.7: Fairness ratio of different routing algorithms at 400 Erlangs](image)

In Figure 3.7, we plot the fairness ratio of the routing algorithms when the network load is fixed at 400 Erlangs. We compute the fairness ratio as follows. At the end of the simulation, we calculate the number of established connection requests that required 1 OC-3, 2 OC-3s, 3 OC-3s, 4 OC-3s, ..., 16 OC-3s of bandwidth. Let $A = \{a_1, a_2, \ldots, a_{16}\}$, where $a_j \in A$ denotes the number of established connection requests that required $j$ OC-3s of bandwidth. The fairness ratio is then expressed as $\frac{a_j}{a_{16}}$ for all $a_j \in A$. An ideal routing algorithm will have a constant value of 1 for this metric as it will establish an equal number of connection requests of varying capacity requirements. It can be observed that WSP and SWP algorithms favor more smaller capacity requests, while OTGA outperforms all the other algorithms.

(iv) **Revenue generated.** Let $b_i$ be a 0 / 1 variable, which takes the value 1 if connection request $i$ is established, otherwise 0. Then the revenue generated, $R$, is proportional to the bandwidth utilized by a connection request times the duration for which the request is active. Therefore, we have
§3.4 Summary

Figure 3.8: Normalized revenue generated by the routing algorithms

\[ R \propto \sum_{i=1}^{2 \times 10^5} b_i \cdot (\beta_i \cdot \Delta_i). \]  

Figure 3.8 shows the normalized revenue generated at different network loads. The efficiency of constructing the routing paths using the cost function is observed as the network load is increased. OTGA generates more revenue in comparison to ASP, SWP and WSP routing schemes.

3.4 Summary

In this chapter, we investigated on-line unicast traffic grooming in WDM-TDM switched optical mesh networks without wavelength conversion capability. Realizing traffic grooming using O/E/O can impact the scalability of the networks. We highlighted the importance of transparent all-optical traffic grooming to avoid O/E/O at the grooming nodes. Using a novel exponential cost function, we proposed a routing algorithm for the concerned problem. We compared and analyzed the performance of the proposed algorithm with the other known heuristics. The experimental results showed that the proposed algorithm outperforms the existing algorithms -
ASP, SWP and WSP in terms of bandwidth blocking ratio, network utilization, fairness and revenue.
Chapter 4

Multicast Routing in WDM Grooming Networks

In this chapter, we consider the on-line multicast traffic grooming problem in WDM grooming mesh networks without wavelength conversion capability. We first introduce the node architecture for sub-wavelength demand multicast traffic grooming in such networks. We then extend the idea introduced in Chapter 3 and show how our novel exponential cost function can be applied to the on-line multicast routing problem in WDM grooming networks. Finally, we show through the performance results obtained by experiments on a representative sized mesh network that the proposed algorithm outperforms the existing algorithms.

The rest of the chapter is organized as follows. The node architecture and the problem definition appear in Section 4.1. The proposed heuristic algorithm is presented in Section 4.2 and the simulation results are discussed and analyzed in Section 4.3. Section 4.4 concludes the chapter.

4.1 Preliminaries

In this section, we first introduce the node architecture used in our study and then formally define the on-line multicast traffic grooming problem. We then provide a brief overview of the existing algorithms for the concerned problem.

4.1.1 Node Architecture

A WDM-TDM switched network that supports multicasting consists of multicast capable switching nodes and OTSIs, with communication fiber links interconnecting the nodes. Each
fiber link carries a certain number of wavelengths and each wavelength is further divided into a number of time slots. The node architecture for sub-wavelength demand multicast grooming in such a WDM-TDM switched network is shown in Figure 4.1. The figure represents a node supporting three links (A, B, C), two wavelengths per link ($\lambda_1$, $\lambda_2$) and three time slots per wavelength ($t_0$, $t_1$, $t_2$). $S_4$ and $S_6$ are unicast sessions utilizing 2 and 1 time slot of bandwidth, while $S_1$, $S_2$, $S_3$, $S_5$, and $S_7$ are multicast sessions utilizing 3, 1, 2, 2 and 2 time slots of bandwidth respectively.

$S_4$ is switched on $\lambda_1$ from input fiber link $C$ to output fiber link $B$. As branching does not occur at the node for multicast sessions $S_1$ and $S_2$ (i.e. $S_1$ and $S_2$ need not be split at the node), they are switched on $\lambda_1$ and $\lambda_2$ from input link $A$ to the same output link. Session $S_3$ arriving on $\lambda_2$ from input fiber link $B$ is dropped locally at the node while Session $S_7$ is added at the node and switched to output link $C$ on $\lambda_1$. To support multicasting in all-optical networks, optical splitters are needed to replicate an incoming optical signal into two or more identical outgoing
§4.1 Preliminaries

signals. In the figure, the splitter bank consisting of optical splitters X and Y perform optical multicasting. Since there are three time slots per wavelength, the optical switch can be set in only three possible settings at any given time. When the switch is set to time slots \( t_0 \) and \( t_1 \), incoming multicast signal \( S_5 \) is split into two identical copies \( C_1 \) and \( C_2 \) by the optical splitter X. Signals can be delayed using Optical Time Slot Interchangers (OTSI), therefore, time slots on an incoming signal can be mapped on to different time slots on the outgoing signal. In the figure, the OTSI introduces a delay of one time slot duration so that \( t_0 \) and \( t_1 \) on one copy of the signal \( S_5 \) (\( C_1 \) on \( \lambda_2 \)) are mapped on to \( t_1 \) and \( t_2 \) at the output link A respectively. When the switch is set to time slot \( t_2 \), \( S_6 \) is switched on \( \lambda_2 \) to the same time slot on output link C.

In this architecture, the output signal weakens because of optical splitting. Hence, they may have to be amplified before the signal is routed to the respective outgoing links. Also, as wavelength conversion is not incorporated in this architecture, the wavelength of an outgoing signal is the same as its incoming wavelength. Hence, the wavelength continuity constraint is obeyed.

4.1.2 Problem Definition

The physical topology of a WDM-TDM switched mesh network is represented by a graph \( G = (V,E) \), consisting of \( |V| = n \) nodes and \( |E| = m \) links interconnecting the nodes. Each link in the physical topology is bidirectional and is modeled as a pair of unidirectional links. \( W = \{\lambda_1, \lambda_2, \ldots, \lambda_w\} \) is the set of available wavelengths in the network. A multicast request \( i \) is represented by a quadruple \((s_i, D_i, \beta_i, \Delta_i)\), where \( s_i \in V \) is the source node, \( D_i \subseteq V \) is the set of destination nodes, \( \beta_i \) is the required bandwidth and \( \Delta_i \) is the duration of the multicast request.

Given the current network state (routes and wavelengths being used by existing traffic), the problem is to construct a minimum cost bandwidth guaranteed tree \( T_i^{\lambda} \) on a wavelength \( \lambda \in W \) that connects \( s_i \) to all the destination nodes in \( D_i \). The aim is to maximize the multicast request acceptance ratio, i.e. the throughput of the network. We assume that the established requests cannot be interrupted and the sequence of incoming multicast requests is not known in advance. We refer to this problem as the Multicast Routing and Wavelength Assignment (MCRWA) problem.
4.1.3 Tree Construction Algorithms

To solve MCRWA, a common approach is to construct a multicast tree connecting the source node to all the destinations in the multicast group. This is the well known Steiner Tree Problem known to be NP-Complete [17]. Various heuristics and approximation algorithms based on the Minimum Spanning Tree (MST) and the Shortest Path Tree (SPT) have been proposed for it.

Generally, routing algorithms can be classified as being static or dynamic [56]. In the static scheme, routes are computed without considering the current network state. The possible routes between source destination pairs are computed a priori, usually based on the shortest path criterion. The dynamic scheme makes use of the current utilization of links and the state of the network in choosing a route. In general, Fixed SPT and Adaptive SPT multicast routing algorithms are used to route multicast traffic [12, 56]. These algorithms are briefly described below.

(i) Fixed Shortest Path Tree (FSPT). A single shortest path based on the hop count is computed between each source destination pair without considering the state of the network. The union of shortest paths from the source node to all the destinations in the multicast group generates the tree.

(ii) Fixed-Alternate Shortest Path Tree (FASPT). This scheme is similar to FSPT, but offers greater flexibility in selecting routes, as a set of routes are assigned to each source destination pair. All shortest paths based on the hop count between source destination pairs are candidate routes for constructing the tree.

(iii) Adaptive Shortest Path Tree (ASPT). The FSPT and FASPT are examples of static routing algorithms whereas ASPT is a dynamic routing algorithm. Here, the routes are computed taking into account the current network state. Only wavelength-links with sufficient bandwidth to accommodate the multicast request are considered for route computation. The path that minimizes the total number of hops between the source node and each destination of the multicast group is then determined. If two paths have the same hop count, then the tie is broken by using the first-fit wavelength assignment policy. The union of these individual shortest paths generates the resultant multicast tree.

To illustrate how heuristic ASPT works, we consider the example shown in Figure 4.2 that represents a five node subnet - 0, 1, 2, 3, 4, of a large wide area mesh network. Assume the
current network configuration of this subnet to be as follows. One wavelength $\lambda_0$ available on links 0 – 1 and 1 – 2, and two wavelengths $\lambda_0$, $\lambda_1$ available on links 0 – 4, 4 – 3 and 3 – 2 respectively. We further assume that the total capacity available on a wavelength is 1, with sessions requiring fractional wavelength capacities. The order of multicast sessions arriving are: $M_1$: 0 $\rightarrow \{1, 2\}$, $M_2$: 0 $\rightarrow \{2, 3\}$ and $M_3$: 1 $\rightarrow \{2, 3\}$. Each session requests bandwidth equivalent to half of the wavelength capacity. The value within the parenthesis along the links in the figure indicate the amount of free bandwidth available on $\lambda_0$ and $\lambda_1$ respectively.

$M_1$ is routed as shown in Figure 4.2 (d) on $\lambda_0$. There are many instances where a destination node in a multicast group may want to transmit information to all the other destinations in the group as well as to the source node. For example, a student participating in a distance learning program may want to ask questions to the instructor and to other fellow students. To facilitate this, the bandwidth requested by a session is reserved along the links in either direction. Thus, following the establishment of $M_1$, $M_2$ is routed as shown in Figure 4.2 (e), also on $\lambda_0$. As a result, node 1 gets logically disconnected from the network along with the links 0 – 1 and 1 – 2, since no further wavelengths are available on these links while $M_1$ and $M_2$ are active. Logical disconnection of nodes result in more and more user requests being blocked. From
the perspective of the network service provider, increased user blocking directly translates to significant revenue loss and poor network utilization. As a result, the new session $M_3$ is blocked due to the lack of available wavelengths to route it.

### 4.2 On-Line Multicast Traffic Grooming Algorithm

In this section, we first give an overview of the proposed algorithm. We then extend the cost function to the context of multicasting and describe how it realizes multicast traffic grooming and load balancing. We finally detail the proposed algorithm.

#### 4.2.1 Overview of the proposed algorithm

We propose a multicast routing scheme, On-line Multicast Traffic Grooming Algorithm (OMTGA), which (i) encourages grooming new sub-wavelength multicast requests onto the wavelengths that are being used by existing multicast traffic, and (ii) incorporates load balancing functionality simultaneously. To do so, we introduce a cost function that takes into consideration the total load on a link and the residual available bandwidth on each wavelength. For every new
incoming multicast request, the Shortest Path Tree heuristic is used to construct the multicast tree. Since wavelength conversion is not allowed, each multicast request can be routed on one wavelength only. Thus, at most $w$ multicast trees can be generated, where $w$ is the total number of wavelengths available in the network. Out of all the resulting wavelengths that can be used to carry the multicast traffic, the wavelength corresponding to the least cost tree is then selected. Here, the cost of a multicast tree is the sum of the cost of all the wavelength-links in the tree. If two trees have the same cost, then the first-fit wavelength assignment policy is employed to break the tie. The bandwidth requested by the multicast session is then reserved along the links in the tree. In the following, we use an example (see Figure 4.3) to explain the idea behind the proposed algorithm.

As in the ASPT scheme, $M_1$ is routed as shown in Figure 4.3 (d) on $\lambda_0$. This increases the load on the links 0–1 and 1–2. Since links 0–4, 4–3, and 3–2 have more wavelengths, it is desirable to use these links to route future requests and prevent the depletion of wavelengths on links 0–1 and 1–2. Therefore, higher costs are assigned to $\lambda_0$ on links 0–1 and 1–2 for subsequent incoming requests. As a result, $M_2$ is routed on $\lambda_0$ on the shortest path tree as shown in Figure 4.3 (e). Now $M_3$ can be successfully established on $\lambda_0$ as shown in Figure 4.3 (f). Therefore, unlike in the Adaptive SPT routing strategy, $M_3$ is not blocked in the proposed routing scheme.

4.2.2 Cost Function

For completeness, the cost function used in the algorithm is described below.

We denote $\Omega$ as the total available bandwidth per wavelength. Let $\mu_{u,v}$ represent the total available bandwidth on a link between nodes $u$ and $v$. Therefore, we have

\[ \forall (u,v) \in E: \quad \mu_{u,v} = w \times \Omega. \]  

(4.1)

For convenience, we normalize the requested bandwidth to the total available bandwidth on a link. Therefore,

\[ \hat{B}_{k}(u,v) = \frac{B_k}{\mu_{u,v}}. \]  

(4.2)

Let $\mathcal{P} = \{T_1, T_2, T_3, \ldots, T_k\}$ be the set of multicast trees assigned to requests 1 through
If a multicast request \( j \) is rejected, or terminates before the arrival of a new multicast request, then \( T_j = \emptyset \), where \( T_j \) is the multicast tree for request \( j \) (\( 1 \leq j \leq k \)). Therefore, the load on link \((u, v) \in E\) after considering request \( k \) is defined as

\[
l^k_{u,v} = \sum_{j=1}^{k} \hat{\beta}_j(u,v). \tag{4.3}
\]

In WDM-TDM networks, bandwidth requirements of requests are expressed in terms of the number of time slots. In this work, we assume that each wavelength is sub-divided into 16 time slots and the capacity of each time slot is equivalent to 1 OC-3 channel. Therefore, the total capacity of each wavelength is equivalent to 1 OC-48 channel, and we have \( \Omega = 16 \) OC-3s.

Let \( \tau_{j,\lambda'}(u,v) \) be the number of OC-3 channels being used on link \((u,v)\) by request \( j \) on wavelength \( \lambda' \in W \). Then, after considering multicast request \( k \), the total number of \( \lambda' \) OC-3 channels being used on link \((u,v)\) is

\[
U^k_{\lambda',u,v} = \sum_{j=1}^{k} \tau_{j,\lambda'}(u,v). \tag{4.4}
\]

When a new multicast request \( i \) arrives, we assign costs to each wavelength \( \lambda' \in W \) on the links in \( E \) as follows.

(i) If the capacity of \( \lambda' \) available on link \((u,v)\) is equal to \( \Omega \), i.e. \( \lambda' \) is not being used by any existing multicast request, then the cost of using \( \lambda' \) on it is

\[
\Psi^\lambda'_{u,v} = a_{\lambda'v} \left( \hat{\beta}_i(u,v) - 1 \right). \tag{4.5}
\]

(ii) Otherwise, \( \lambda' \) is currently being used by existing multicast requests, and two cases arise.

Case 1: If the residual capacity of \( \lambda' \) on link \((u,v)\) is less than \( \Omega \), but no less than the
requested bandwidth $\beta_i$, then the cost of using $\lambda'$ on it is
\[
\psi_{u,v}^{\lambda'} = \frac{U_{u,v}^{\lambda'} \left( \frac{\beta_i}{\lambda'(u,v)} - 1 \right)}{R_{\lambda'}(u,v)},
\]
(4.6)

where $a$ and $b$ are appropriately chosen constants. Here, $R_{\lambda'}(u,v)$ is the residual capacity of $\lambda'$ on link $(u,v)$ after considering the first $k$ requests, and is given by
\[
R_{\lambda'}(u,v) = 1 - \frac{U_{u,v}^{\lambda'}}{\Omega}.
\]
(4.7)

Importantly, observe that, to realize load balancing and grooming interests, the constants $a$ and $b$ in the cost function must be greater than 1.

Case 2: If the residual capacity of $\lambda'$ on link $(u,v)$ is less than $\beta_i$, then $\psi_{u,v}^{\lambda'} = \infty$, which means it cannot be used to construct the multicast tree.

Note that, from Equation (4.5), if $\lambda'$ is not being used by any existing multicast request on link $(u,v)$ (i.e. full wavelength capacity of $\lambda'$ is available on link $(u,v)$), then the cost assigned to it represents the change in its relative load that would occur if it were to be used by the new multicast request [1]. From Equation (4.6), if the residual capacity of $\lambda'$ on link $(u,v)$ is less than $\Omega$, but no less than the requested bandwidth $\beta_i$, then the cost of $\lambda'$ on this link is expressed as a function of the change in its relative load and the residual capacity of $\lambda'$. In other words, load balancing is realized by increasing the cost of using wavelengths on heavily loaded links, thus discouraging them from being used by new multicast requests. To encourage grooming new multicast requests onto the wavelengths that are already being used by existing multicast traffic, the costs of these wavelengths are further decreased by a factor of their residual capacities. Therefore, among the wavelengths that are currently being used on a link, we encourage grooming on the wavelength that has the highest residual capacity. This minimizes the logical disconnection of nodes from the network and achieves our objective.
4.2.3 Algorithm

Having defined the cost function, we are ready to introduce the detailed algorithm as follows.

Once a new multicast request arrives, the algorithm is executed to determine whether the request is accepted.

Algorithm OMTGA\((s_i, D_i, \beta_i)\)

begin
\(C_{\text{MAX}} \leftarrow \infty; \lambda \leftarrow \text{nil}; T_i^\lambda \leftarrow \text{nil};\)
/* \(C_{\text{MAX}}\) is the total cost to establish request \(i\), \(\lambda\) is the resulting wavelength on which to */
/* route request \(i\), \(T_i^\lambda\) is the multicast tree for request \(i\), \(\Omega\) is the total capacity per */
/* wavelength */

Step 1. Tear down and free the wavelength resources used by all the multicast requests that terminate before the arrival of request \(i\).
\(\forall (u, v) \in E : \hat{\beta}_i(u, v) \leftarrow \frac{\beta_i}{\mu_{u,v}}\)

Step 2. for each wavelength \(\lambda' \in W\) do

Step 3. Compute \(RC(u, v, \lambda')\), the residual capacity of \(\lambda'\) on link \((u, v) \in E\)

Step 4. if \(RC(u, v, \lambda') = \Omega\) then \(\Psi_{u,v}^{\lambda'} \leftarrow \text{cost from Equation (4.5)}\)
else if \(\hat{\beta}_i \leq RC(u, v, \lambda') < \Omega\)
then \(\Psi_{u,v}^{\lambda'} \leftarrow \text{cost from Equation (4.6)}\)
else \(\Psi_{u,v}^{\lambda'} \leftarrow \infty\)
endif;
endif;

Step 5. Find the shortest path from \(s_i\) to each destination in \(D_i\) w.r.t costs \(\Psi_{u,v}^{\lambda'}\) using Dijkstra's algorithm. The union of individual paths from the source node to each destination node constitutes the multicast tree \(T_{(\lambda',\cdot)}\).

Step 6. Let \(c_i\) be the total cost of constructing the tree \(T_{(\lambda',\cdot)}\). If a path does not exist between the source node to every destination node in \(D_i\), then \(c_i \leftarrow \infty;\) otherwise \(c_i\) is the sum of the cost of all the links in \(T_{(\lambda',\cdot)}\).

Step 7. if \(c_i < C_{\text{MAX}}\) then
\(C_{\text{MAX}} \leftarrow c_i; \lambda \leftarrow \lambda'; T_i^\lambda \leftarrow T_{(\lambda',\cdot)}\)
endif;
endfor;
§4.3 Simulation Study

Step 8. if $C_{\text{MAX}} \neq \infty$ then

\begin{align*}
\text{for each link } (u, v) \in T_i^\lambda & \\
RC(u, v, \lambda) & \leftarrow RC(u, v, \lambda) - \beta_i \\
RC(v, u, \lambda) & \leftarrow RC(v, u, \lambda) - \beta_i \\
\end{align*}

endif;

return multicast tree $T_i^\lambda$

endif;

Step 9. return "request blocked"

end.

We now analyze the computational complexity of the proposed algorithm. The single-source shortest path tree rooted at the source can be found using Dijkstra’s algorithm, which can be implemented in $O(m + n \log n)$ time using Fibonacci heaps. Therefore, the time complexity of the algorithm is $O(w(m + n \log n))$ as it is run once for each $\lambda' \in W$.

4.3 Simulation Study

In this section, we first introduce the simulation environment and then present the experimental results. We analyze the performance of OMTGA using various network performance metrics and compare the results with the other existing algorithms.

4.3.1 Simulation Environment

To evaluate the performance of the proposed algorithm, we conducted experiments on the representative sized mesh network shown in Figure 3.3. Each fiber link carries 16 wavelengths. All the nodes in the network have the architecture shown in Figure 4.1. We further assume that the wavelength continuity constraint is imposed. The bandwidth required by multicast requests is uniformly distributed between 1 OC-3 and 16 OC-3s. The request arrival is a Poisson process and its duration is exponentially distributed. Each node in the network is given equal probability of being the source node. The size of each multicast group is a random number uniformly distributed between 2 and 22. The nodes in the destination set are also uniformly distributed across the network. The load (in Erlangs) on the network is increased
by increasing the average connection holding time. We simulate 100,000 requests to obtain the network performance under a certain network load. The simulations were performed on a Linux PC with a 2.8 GHz Pentium IV processor and 512 MB of memory.

![Performance improvement offered by OMTGA relative to ASPT](image)

Figure 4.4: Percentage improvement offered by OMTGA for different values of $a$ and $b$

To identify the $(a,b)$ value pair that gives good network performance consistently across all the network loads, we conducted experiments by iteratively varying $a$ and $b$ in the cost function and recording the improvement that OMTGA offered relative to ASPT. The improvement is measured in terms of the total number of multicast requests established by OMTGA and ASPT. $a$ varies from 4 to 15 and $b$ varies from 2 to 14. The experiment is repeated at four different network loads - 200, 350, 500 and 650 Erlangs. Figure 4.4 shows the percentage improvement offered by OMTGA when $a$ varies from 13 to 15 and $b$ varies from 8 to 14 respectively. The improvement seen by other combination of values is lower than that shown in Figure 4.4, omitted for brevity. It can be seen from the figure that a few $(a,b)$ pairs give consistently good performance at different network loads. $(13, 12)$, $(14, 13)$ and $(15, 12)$ are a few sample values. In all our experiments, we fix the constants $a$ and $b$ at 15 and 12 respectively. These values are not altered as the network load varies.
4.3.2 Experimental Results

We compared the performance of OMTGA with the other existing algorithms - FSPT, FASPT and ASPT. The metrics used to measure the performance of the algorithms are: (i) multicast request acceptance ratio, (ii) average resource utilization efficiency, and (iii) normalized revenue generated.

(i) **Multicast request acceptance ratio.** The request acceptance ratio curves of different routing algorithms are shown in Figure 4.5.

![Multicast Request Acceptance Ratio](image)

**Figure 4.5:** Percentage of multicast requests accepted by different routing algorithms

It can be observed from the figure that, when the network load (in Erlangs) is small, the percentage of requests accepted by OMTGA and ASPT is similar. This is because, at low loads, the average connection holding time is less. The costs assigned to all the links derived from the cost function are nearly identical. Therefore, the behavior of OMTGA, and hence the percentage of requests accepted by it is similar to ASPT.

With the increase in the average connection holding time, the network load also increases. The exponential nature of the cost functions in Equations (4.5) and (4.6) prevent the depletion of wavelengths on heavily loaded links by assigning to it, costs, that are significantly higher than the costs assigned to lightly loaded links. This in turn leads to creation of routing paths...
that are distributed among the links evenly. From the figure it can be seen that, as the network load increases, the percentage of multicast requests that are accepted decreases. However, the percentage of requests accepted by OMTGA is higher than the percentage of requests accepted by the ASPT heuristic, thereby offering better performance.

To study the performance gain of the tree construction algorithms, we assume that the normal case of serving multicast requests is by using the ASPT heuristic. Therefore, the performance gain of an algorithm (say OMTGA) relative to ASPT can be calculated as follows.

Let $M_{E_{ASPT}}$ and $M_{E_{OMTGA}}$ be the total number of multicast requests established by the ASPT and OMTGA routing schemes respectively. Then, the performance gain of OMTGA, $U_{OMTGA}$, can be defined as

$$U_{OMTGA} = \frac{M_{E_{OMTGA}} - M_{E_{ASPT}}}{M_{E_{ASPT}}} \times 100$$  \hspace{1cm} (4.8)

The performance gain of FSPT and FASPT are defined similarly.

![Relative Performance Gain](image)

**Figure 4.6**: Performance gain relative to ASPT

Figure 4.6 shows that the gain is negative if FSPT and FASPT are used, suggesting the inefficiency of these two schemes relative to ASPT. Recall that the network load is increased
with the increase in the average connection holding time. Consequently, since the behavior of OMTGA and ASPT are similar at lower loads, we observe that the performance gain obtained by OMTGA is relatively small (about 5%). However, as the network load is increased, the load balancing nature of the cost function with grooming interest efficiently routes multicast traffic and achieves high performance gains of about 15% - 18%.

(ii) **Average Resource Utilization Efficiency (RUE).** To understand how the allocated wavelength channels are utilized, we use the resource utilization efficiency metric. RUE represents how efficiently multicast traffic is routed and groomed. At any instant of time, RUE is computed as the total network carried traffic (in OC-3 units) divided by the total network capacity allocated (total number of wavelength-links allocated times 48).

The RUE is computed after every 25 request arrivals and is averaged over 100,000 multicast requests. Figure 4.7 shows the resulting average resource utilization efficiency (RUE) curves as the network load is varied. The higher the RUE of an algorithm, the better is the efficiency with which the algorithm routes and grooms multicast traffic. From the figure it can be observed that OMTGA has the highest RUE, followed by ASPT, FASPT and FSPT. The algorithm not only performs load balancing, but also efficiently packs new sub-wavelength
multicast requests on to the wavelengths that are already being used by existing traffic. This explains why OMTGA achieves high request acceptance ratios shown in Figure 4.5.

(iii) Revenue generated. Let \( b_i \) be a 0 / 1 variable, which takes the value 1 if connection \( i \) is established, otherwise 0. Then the revenue generated, \( R \), is proportional to the bandwidth utilized by a request times the duration for which the request is active. Therefore, we have

\[
R \approx \sum_{i=1}^{1 \cdot 10^5} b_i \cdot (\beta_i \cdot \Delta_i).
\]  
(4.9)

Figure 4.8: Normalized revenue generated by the routing algorithms

Figure 4.8 shows the normalized revenue earned at different network loads. The efficiency of constructing the multicast trees using the cost function is observed as the network load is increased. OMTGA generates more revenue in comparison to ASPT, FASPT and FSPT routing schemes.

4.4 Summary

In this chapter, we investigated the on-line provisioning of sub-wavelength multicast demands in a WDM-TDM switched mesh network without wavelength conversion capability. Using a
novel exponential cost function, we introduced the OMTGA algorithm for efficient multicast traffic grooming. We compared and analyzed the performance of the proposed algorithm with the other well-known heuristics - FSPT, FASPT and ASPT. Our experimental results showed that OMTGA outperforms the existing algorithms in terms of request acceptance ratio, performance gain, average resource utilization efficiency and revenue.
Wavelength Division Multiplexing (WDM) optical networks have emerged as the most promising candidate for next-generation high-speed backbone networks. A connection request between two endpoints is established by finding a feasible routing path and a wavelength to carry the traffic. This is referred to as the Routing and Wavelength Assignment (RWA) problem. Since wavelengths are the critical resources in optical networks, assigning them efficiently to connection requests is of paramount importance. As such, routing in WDM optical networks is fundamentally different from routing in traditional electronic networks. This limits the use of routing algorithms designed for traditional electronic networks and calls for the design of new RWA algorithms.

In Chapter 2, we considered the multiple end-to-end delay constrained multicasting problem in a multi-hop WDM optical network. Multicasting is an important service that has gained prominence and forms an integral part of communication networks. A key requirement of multimedia applications is the timely delivery of information. A closely related Quality of Service (QoS) metric is the end-to-end delay bound between each source-destination pair. The end-to-end delay metric is used to guarantee the real-time nature of multicast applications such as video-conferencing and distance learning. For a given source-destination pair, it denotes the maximum permissible delay before which the traffic originating from the source node must reach its corresponding destination node. We developed an Integer Linear Program formulation for the problem with the objective to minimize the total cost of establishing a set of $k$ multicast sessions. In minimizing the total cost, we showed why we need to consider the cost of wavelength utilization and the cost of wavelength conversion. Also, in bounding the end-to-end delay, we showed the importance of considering transmission delays on links and the delays incurred due to wavelength conversion at the intermediate nodes. We evaluated the
Conclusions and Future Work

richness of our formulation using the simulation results derived from the real-world NSFNET backbone network. In the future, we propose to extend the work by developing LP relaxation techniques and heuristics to obtain good suboptimal solutions quickly.

There is a huge mismatch in the available capacity on a single wavelength channel and the bandwidth required by modern day applications. To make better use of the available wavelength capacity, multiple connection requests are multiplexed onto a single high capacity wavelength channel. This is called traffic grooming. An effective and practical all-optical approach to traffic grooming is to use Time Division Multiplexing (TDM). We introduced the concept of WDM-TDM switched networks also called WDM grooming networks. In Chapter 3, we presented a node architecture for sub-wavelength demand traffic grooming involving all-optical switches and Optical Time Slot Interchangers (OTSi). We then introduced a novel exponential cost function that not only encourages grooming new connection requests onto the wavelengths that are already being used by existing traffic, but also performs load balancing functionality. We then studied on-line routing in WDM grooming networks and presented the On-line Traffic Grooming Algorithm (OTGA). Using the experimental results obtained by simulation on a practical sized mesh network, we compared and analyzed the performance of OTGA with the other existing algorithms - Widest Shortest Path (WSP), Shortest Widest Path (SWP) and Available Shortest Path (ASP). The experimental results showed that OTGA outperforms these existing algorithms in terms of bandwidth blocking ratio, network utilization, fairness and revenue.

In Chapter 4, we extended the idea first proposed in Chapter 3 to the on-line multicast routing problem in WDM grooming networks. Multicast traffic grooming is an emerging field and has received very little attention in the literature. This is indeed a very practical problem and is expected to receive significant attention in the future. Multicasting in WDM networks can be efficiently setup using optical splitters due to their inherent multicasting capability (splitting of light). Using optical splitter banks and OTSi, we introduced the node architecture for sub-wavelength demand multicast traffic grooming in WDM-TDM switched networks. It is well-known that multicast routing is an NP-Complete problem. In general, Fixed Shortest Path Tree (FSPT), Fixed-Alternate Shortest Path Tree (FASPT) and Adaptive Shortest Path Tree (ASPT) heuristics are used to design multicast trees. We extended the novel exponential cost function and introduced the On-line Multicast Traffic Grooming Algorithm (OMTGA).
We showed how OMTGA can be used to solve the on-line multicast traffic grooming problem and illustrated its advantages over the ASPT heuristic. Finally, using simulation results we compared the performance of OMTGA with the FSPT, FASPT and ASPT heuristics. The simulation results showed that OMTGA outperforms these well-known existing algorithms.

It will be very interesting to establish upper bounds on the constants $a$ and $b$ used in the cost function. Currently, these constants are iteratively varied and the performance improvement is recorded. Subsequently, we identify the best possible combination that consistently provides good results across the network loads. Establishing theoretical upper bounds will make the formulation more robust and is a subject for future research. We also propose to extend the traffic grooming algorithm to the case where different connection requests have different priorities associated with them.
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