Dynamic traffic grooming in IP/MPLS over WDM networks

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**DYNAMIC TRAFFIC GROOMING IN IP/MPLS
OVER WDM NETWORKS**

**CHEN BIN
SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING
2007**

Dynamic Traffic Grooming in IP/MPLS over WDM Networks

Chen Bin

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
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Doctor of Philosophy

2007

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Abstract

IP/MPLS over WDM network is a promising candidate for the next generation optical Internet network. To efficiently operate such a network, traffic grooming is important in inter-working between the WDM network that supplies bandwidth at the wavelength granularity, and the attached client networks, e.g. the IP/MPLS network, that usually require connections of sub-wavelength granularity. Among the interconnection models between the IP/MPLS layer and the optical layer, the overlay model is seen as the most practical model for near-term deployment. In this work, we focus on investigating and proposing novel and practical dynamic traffic grooming policies in IP/MPLS over WDM mesh networks under the overlay model.

It is well known that alternate routing is a good way to exploit the idle bandwidth in the network. However, this may cause the spread of congestion. Based on the observation of this problem, we propose to set up a new lightpath for the congested link in the IP/MPLS layer to solve this problem. In this case, to decide when and where to set up a lightpath becomes important to efficiently use network resource and improve the overall network performance. We propose a Path Inflation Index (PII) to monitor the congestion level caused by alternate routing. With this parameter, the Path Inflation Control (PIC) policy can trigger a lightpath establishment according to the network congestion state. The simulation results show that the PIC policy can achieve lower blocking ratio than other policies.

Providing differentiated services is believed to be the right solution to increase the network provider's profits. We choose to provide differentiated blocking ratios for different classes of LSP requests. Our method is to block a low priority LSP request if a lightpath can not be set up to avoid the congestion spread caused by using an alternate path. Further more, an Average Path Inflation Index (APII) is also proposed to monitor the traffic load to avoid summarily blocking the lower priority traffic even when the traffic load is light. The simulation results show that the proposed approaches work well in the multi-class traffic case.

The blocking performance of IP/MPLS over WDM networks under the overlay model can be improved if the optical layer can get more topology information of the IP/MPLS layer. We adapt the conventional saturated cut method to extract the IP/MPLS layer connection information related to a newly arrived LSP request. With this method, the optical layer can calculate the shortest lightpath between two node groups rather than between end nodes of an LSP request. It is shown that setting up lightpaths for saturated cuts in the IP/MPLS layer can improve network performance significantly. Heuristic modifications are also presented which provide almost the same level of performance with much lower complexity.

With the increasing demands of transmitting real-time multimedia, multicasting is becoming more important by now. Grooming multicast traffic into wavelength channels will be important for efficiently using the future Internet. We adapt our proposed unicast

traffic grooming methods for handling the multicast case. Different algorithms for multicast traffic grooming are proposed and compared using simulation.

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List of Acronyms

ASON	Automatically Switched Optical Network
AL	Alternate Lightpath
ASL	Absolutely Shortest Lightpath
AP	Alternate Path
APII	Average Path Inflation Index
ASP	Absolutely Shortest Path
ASPR	Alternate Shortest Path Routing
ATM	Asynchronous Transfer Mode
CBR	Constraint-Based Routing
CR-LDP	Constraint Routing Label Distribution Protocol
DXC	Digital Cross-Connects
EDFA	Erbium-Doped Fiber Amplifier
FEC	Forwarding Equivalence Class
G.ASTN	Global. Automatically Switched Transport Network
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
ILF	IP Layer First
ILP	Integer Linear Programming
IP	Internet Protocol
ITU	International Telecommunication Union

ITU-T	The ITU Telecommunication Standardization Sector
ISP	Internet Service Provider
LSP	Label Switched Paths
LSR	Label Switched Router
MEMS	Micro Electro Mechanical System
MILP	Mixed Integer Linear Programming ()
MOCA	Maximum Open Capacity Routing Algorithm
MPLS	Multi-protocol Label Switching
OADM	Optical Add/Drop Multiplexer
OHF	One Hop First
OIF	Optical Internetworking Forum
OLF	Optical Layer First
OR	Optical Receiver
OSPF	Open Shortest Path First
OT	Optical Transmitter
OXC	Optical Crossconnects
PII	Path Inflation Index
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RSVP-TE	Resource Reservation Setup Protocol with Traffic-engineering Extension
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing

TRR	Trunk Reservation Routing
TTL	Time-to-Live
UNI	User Network Interface
WDM	Wavelength Division Multiplex
WMUX	Wavelength Multiplexer

Chapter 1 Introduction

Traffic demands in communication networks have been growing rapidly because of the introduction of various bandwidth intensive services in Internet/Intranet-based applications. Most carriers report that data traffic has already overtaken or soon will overtake their voice traffic counterpart. In [1], the author has given a detailed analysis and made a convincing claim that the Internet traffic is approximately doubling every year. With the advent of multi-protocol label switching (MPLS) technology, IP networks can now also provide services with QoS guarantees and traffic engineering capabilities. These networks will provide not only the traditional best effort services such as electronic mail (email), File Transfer Protocol (FTP) and the World Wide Web (WWW) but can also support delay sensitive services such as voice, video on demand, video conferencing, and interactive virtual reality systems. With increasing richness of multimedia content and multimedia applications, not only would the Internet become more heavily loaded and highly utilized, the growth rate of its capacity must also keep increasing in pace to cater to this increased demand.

In parallel with the fast growth in Internet traffic, advances in wavelength division multiplexing (WDM) optical fiber transmission technology also promise a steady increase in the total data-rate that can be supported in a single optical fiber. Current

commercial WDM systems offer 4 to 64 wavelengths at 2.5 or 10 Gbps per wavelength, which amounts to approaching 1 Tbps in total capacity. WDM transmission systems in research laboratories have already exceeded multi-terabits in a single optical fiber [2]. This ability to provide very high capacities will make WDM the technology of choice for the Internet in the foreseeable future.

Present generation optical networks use optical technology only for transmitting data over point-to-point links. Although this approach increases the link bandwidth by using WDM, it does not solve the problem of network bottlenecks due to the exponential traffic growth driven by Internet-based services. It only shifts the bottleneck problem from the link to the electronic router. With the increasing maturity of optical crossconnect (OXC) and optical add/drop multiplex (OADM) technologies, a solution to this problem is to transport IP traffic directly over optical networks. In this new approach, some of the switching and routing functions, which have been performed by electronics, are incorporated into the optical domain. Such an all-optical communication channel between two nodes in the network is referred to as a *lightpath*. If this approach is followed, IP/MPLS over WDM will be the technology dominating future Internet expansion.

1.1 Motivation

Most of today's optical networks are based on the ring topology [3] and were designed to handle voice traffic. These traffic patterns are hierarchical in nature. Hierarchically organized rings are extremely appropriate architectures for such traffic, because they are

based on the fact that call requests are multiplexed up into the hierarchy. However, data traffic is not hierarchical in nature. Data traffic tends to be random, arbitrary, unpredictable, and meshed in nature where the source and destinations are not known apriori. A mesh topology, where nodes are interconnected through multiple paths, is better suited to support such data traffic patterns.

Fig. 1.1 Rings: Duplicated working and protection segments

Fig. 1.2 Mesh: Consolidate nodes and facilities and share protection

For the rings in **Fig. 1.1**, each portion of the overall circuit's route must be separately protected, thus half of the capacity of the overall network is sacrificed in the name of protection. By contrast, meshes do not rely on a reserved, dedicated backup. Instead, the meshes shown in **Fig. 1.2** can simply divert the traffic to a new route that avoids the

failed link. This method will reduce protection requirements from the 1:1 (protection:working for rings) to 1:2 or 1:3 (for a meshed network), effectively increasing the capacity available for traffic [4] [5]. It is expected the next-generation optical transport network will be based on an irregular mesh topology, which will make it much easier to scale [5] and support Internet services. Therefore, we give our focus to mesh networks in this study.

The bandwidth of a wavelength is close to its peak electronic transmission speed and has steadily increased from OC-48 (2.5 Gbps) to OC-192 (10 Gbps), and is expected to increase up to OC-768 (40 Gbps). At the same time, networks are required to provide services to individual users who work at much lower bit rates than that is available on the wavelength channel. If the entire bandwidth of a wavelength channel is allocated to a low-speed connection, a large portion of its transmission capacity will be wasted. This is a major challenge in the implementation of the IP/MPLS-over-WDM approach, demanding an effective way to bridge the gap between the electrical IP/MPLS layer and the optical WDM layer.

In order to use the network resources efficiently, low-speed traffic streams need to be efficiently multiplexed, or “groomed,” onto the high-speed wavelength channels [6-10]. Considerable research on traffic grooming in WDM/SONET rings has been reported in the literature [11-15]. With the advent of optical networks with mesh topologies, traffic grooming in a WDM mesh network is also becoming a topic of increasing interest [7, 16, 17].

In the next generation optical network, a lightpath can be established between two nodes by configuring the transmitter, receiver and intermediate optical crossconnects (OXCs) along the path for a one-electrical hop communication channel [18]. The virtual topology will then consist of the lightpaths established in the optical network. This will decide the topology and capacity of the upper layers, e.g. IP/MPLS layer. The traffic grooming problem is closely related to the problem of how best one can mesh this virtual topology according to the traffic distribution in the higher IP/MPLS layer. For this, the set of connection requests from the IP/MPLS layer may either all be given in advance (static traffic), or will be given one at a time (dynamic traffic). Based on these, the traffic grooming problem will then be classified either as a static traffic grooming problem or as a dynamic traffic grooming problem.

In the static traffic grooming problem, a traffic matrix is given. Each entry in the traffic matrix is viewed as a different commodity. A logical complete graph is created where the nodes represent the actual physical nodes, but the links in the logical graph represent potential lightpaths connecting the nodes. The flow problem is solved over the logical complete graph with the goal of minimizing the congestion or maximizing the throughput [4, 7, 17].

It is anticipated that the introduction of automatic switched optical networks (ASONs) together with the Generalized Multiprotocol Label Switching (GMPLS) will allow short-term bandwidth contracts since the transaction cost will become very low [19]. This will significantly change the way the carriers sell bandwidth. Users will obtain high

bandwidth services as and when required by just pointing and clicking. This would lead to new applications and services such as those using “bandwidth on demand” and “bandwidth trading”. For handling these, future networks should be able to respond dynamically to traffic demands which would generally be unpredictable in nature [20]. This has led to the current interest in dynamic traffic grooming. Reconfiguring the underlying optical network according to the traffic changes in the upper layers is crucial to maximize the carriers’ revenue and maintain the network stability. The methods for solving a static traffic grooming problem may not be applicable here. One reason is the time consuming characteristics of the algorithm for the static traffic grooming [7]. The other reason is that the dynamic traffic grooming must consider the system constraints. In the static traffic grooming, we can collect all the information of the system and the traffic for optimization. In the dynamic traffic grooming case, different layers may not share their topology information to each other. It is also shown in [7] that the network throughput in the static traffic grooming case can be improved by the variation of the traffic flow sequence. However, the dynamic traffic grooming network has to accept the traffic flow when it arrives. Therefore, fast and efficient on-line algorithms need to be designed for improving the efficiency of future IP/MPLS over WDM networks under a dynamic traffic model. Motivated by this, we aim to propose and develop new efficient traffic grooming approaches for dealing with dynamic traffic demands in future IP/MPLS over WDM mesh networks.

1.2 Objectives

In the dynamic situation, traffic grooming in IP/MPLS over WDM networks is not only a two-layer routing problem but also an admission control problem for the optical layer. Even though lightpaths provide huge bandwidth for the IP/MPLS layer, the number of wavelengths and transceivers in the optical layer is limited and the method of establishing lightpaths has a major impact on the performance of the traffic-grooming policies. A *traffic grooming policy* is mainly concerned about how to trigger a virtual topology reconfiguration or a lightpath establishment so that the overall network performance is optimized. The main objectives of this thesis are:

- *To investigate and propose novel and practical dynamic traffic grooming policies that provide better performance than existing ones* - The criterion we choose is the network-blocking ratio, which determines the network capacity and the carriers' revenue. It may also be noted that, under certain restrictions, even other optimization objectives may be converted to the blocking ratio.
- *To provide differentiated services for the dynamic traffic grooming. Instead of buying a large amount of redundant capacity for supporting all requests, most service providers choose to devise a network with a reasonable size* - In such a network, when the traffic intensity is high, some traffic of low priority will be blocked though the stability of the overall network will still be maintained.

Providing differentiated services would be important for running a network economically.

- *To exploit the topology information available under the overlay interconnection model for improving the network performance further* - The overlay model of IP/MPLS over WDM networks is the simplest and most feasible interconnection model to use. Following this model, the IP/MPLS layer and optical layer are operated independently. This makes them protocol independent and facilitates their implementation. However, the topology information in each layer cannot be shared in this model. The network cannot fully utilize available resource in both layers. For example, connection requests in the IP/MPLS layer may get blocked even when there are enough idle wavelength resources in the optical layer. If we can utilize such “invisible” wavelength resources, then we can increase the capacity of the network without adding new equipment or resources.
- *To propose novel and practical dynamic multicast traffic grooming policies that provide good performance.* Applications that require multicast capability (either point-to-multipoint as in distributional video or multipoint-to-multipoint as in video conferencing, online collaboration, and others) will be an integral part of future broadband services. Grooming multicast traffic into wavelength channels will be important for efficiently using the future Internet.

1.3 Major Contribution of the Thesis

The original contributions of this thesis are as follows:

- *The proposal of a Path Inflation Control (PIC) policy for dynamic traffic grooming* - With the MPLS protocol, traffic flows are routed according to the network link state so that they can best exploit the network's bandwidth resource. However, this may cause congestion to spread in the network. In traditional telephone networks, trunk reservation [21] tackles this kind of congestion by allowing a link to accept alternatively routed calls only when the number of idle circuits on the link is more than the trunk reservation parameter. This kind of alternative routing has been shown to improve the performance of the telephone network. However, since LSP requests do not have fixed bandwidths like telephone circuits, it is difficult to define an analogous reservation parameter for the IP/MPLS over WDM case. An alternative would be to dynamically set up a new lightpath to provide bandwidth for the congested link before the congestion spreads to the other links. We propose a Path Inflation Index (PII) to evaluate the congestion degree in the network and trigger setting up a lightpath if the PII is bigger than a pre-defined threshold value. The performance of the PIC policy is compared with other dynamic traffic grooming policies and it is shown to have the best performance. (Chapter 3)

- *The proposal of a new method based on the PIC policy to provide differentiated blocking ratio for different classes of traffic in IP/MPLS over WDM networks -*

One approach to provide different blocking ratios for different classes of traffic is to selectively block lower priority traffic. This would keep additional resources available for the higher priority classes so that these LSP requests encounter less blocking. Since LSP requests arrive randomly, we require some rationale that must be followed to block traffic with the lower priority classes while allowing those with higher priority. Moreover, we need to strike a balance between providing better service (i.e. less blocking) while keeping path inflation low. This is necessary as otherwise overall service to other (even higher class) traffic flows would also be severely degraded. We choose to block a low priority LSP request when routing it can lead to a relatively large PII value in the IP/MPLS layer but when a suitable lightpath cannot be set up to alleviate such congestion. We also propose an Average Path Inflation Index (APII) to monitor the traffic load in a particular path to avoid the adverse behavior of blocking the lower priority traffic even when the traffic is low. Our simulation results show that the proposed approaches work well in handling traffic of different priority classes and result in good overall performance. (Chapter 4)

- *The proposal of applying saturated cut (SC) method [22] in the dynamic traffic grooming -* Even though lightpaths provide huge bandwidth for the IP/MPLS layer, the number of wavelengths and transceivers in the optical layer is limited and hence the method of establishing lightpaths has a major impact on the

performance of the traffic-grooming policies. In the policies mentioned earlier, the network sets up a lightpath only between the end nodes of an LSP request. If the entire topology information available in the overlay model is used then we can further improve the performance of our lightpath establishment strategy. This has been explored in this work. We have applied the SC method to the traffic grooming policies proposed by us earlier, i.e. the IP layer first (ILF) and PIC policies. We have also proposed a new heuristic Partial SC scheme which has been shown to perform well. The simulation results show that the network blocking performance can be improved by an order of magnitude or more with this approach. (Chapter 5)

- *Proposal of two algorithms to do multicast traffic grooming based on the ILF and saturated cut methods* - The simulation results show that by applying the saturated cut method to handle multicast traffic grooming, the network performance improves significantly. This is particularly observed when the number of destination nodes is relatively small as compared to the total number of nodes in the network. (Chapter 6)

1.4 Organization of the Thesis

The rest of the thesis is organized as follows. In Chapter 2, the IP/MPLS over WDM network and its two major traffic-engineering tools, e.g. label switched paths (LSP) and lightpaths are introduced. The traffic-grooming problem is described concisely. A literature review of the static and dynamic traffic grooming problems is also given in this part.

Chapter 3 presents the Path Inflation Control (PIC) policies. Numerical studies are carried out to examine the performance of these PIC policies and compare it with other traffic grooming policies using two typical network topologies, e.g. NSF and COST239.

Chapter 4 extends the proposed path inflation control strategy to handle networks where the offered traffic consists of flows with different priority classes. In such a network, differentiated services have to be provided, depending on the class of the traffic. We propose algorithms for doing this and study their performance by simulating networks with two and three classes of traffic.

In Chapter 5, we adapt the conventional saturated cut method to enhance the lightpath establishment capability of the various traffic grooming policies proposed earlier. Heuristic modifications are also presented which provide almost the same level of performance with much lower complexity.

In Chapter 6, we propose two different lightpath establishing strategies in the multicast traffic-grooming situation. Computer simulations have been conducted to evaluate the network blocking performance.

Finally, the thesis is concluded in Chapter 7 with recommendation for future research

Chapter 2 Literature Review

In this chapter, we provide an overview of traffic grooming in WDM networks. After giving an introduction of enabling optical technologies, we describe the IP/MPLS over WDM network and related traffic engineering tools. We then discuss the primary issues involved in traffic grooming and review the existing work that has been carried out in the field of traffic grooming.

2.1 Enabling Technology in Optical Networks

Wavelength-division multiplexing (WDM) is the dominant technology for exploiting the huge bandwidth of optical fibers and other optical components. It uses multiple wavelengths to transmit different data streams in a fiber. The basis of WDM is to use multiple sources operating at slightly different wavelengths with the bandwidth of each channel matching the electronic data rate. With the development of WDM technology, the transmission capacity of optical systems has increased tremendously to several hundred gigabits; even a single fiber transmission capability of 5 Tbps has been recently reported [2].

Photonic amplifiers provide the extra power budget needed to overcome fiber losses and signal losses due to different elements in the network. Since the mid-1990s, a

combination of the Erbium-Doped Fiber Amplifier (EDFA) and WDM has been used to boost fiber capacity to even higher levels and to increase the transmission distance.

Fig. 2.1 A four-channel point-to-point WDM transmission system with amplifiers.

Fig. 2.2 A MEMS-based OXC structure extracted from Ref. [23]

A four-channel “WDM solution” is shown in Fig. 2.1 where a WDM multiplexer combines four independent data streams, each on a unique wavelength, and sends them on a fiber; a demultiplexer at the fiber’s receiving end separates out these data streams.

Optical crossconnects (OXC) are switching systems that would be used to provide wavelength routing capability. An OXC structure using the micro electro mechanical system (MEMS) approach is shown in Fig. 2.2. Suitably configured by the control unit, the tiny reflective surfaces of the MEMS can redirect light signals arriving at different input ports to different output ports. Wavelength conversion allows the incoming optical signal on a particular wavelength to be shifted to a different outgoing wavelength.

Fig. 2.3 The schematic of an OADM

An optical add/drop multiplexer (OADM), as shown in Fig. 2.3, would be able to dynamically add, drop or pass through any single or multiple wavelength channels. In general, at least several active optical components, optical switches or tunable filters, are included in the OADMs. These may then be used to manually or automatically reconfigure the wavelengths that are to be added or dropped.

Wavelength conversion allows an optical signal on a wavelength to be shifted to a different wavelength. The wavelength converters make it possible to assign wavelengths on a link by link basis or on a sub-network basis, thereby relaxing the requirements for the wavelength to be maintained the same throughout the whole network. Moreover, wavelength conversion eases recovery from link or node failures

by allowing for local rather than global reconfigurations in the network. Networks will become more scalable if wavelength converters are used and their capacity will also increase [24].

2.2 IP/MPLS over WDM Network

The history of optical communication has been mostly about transmission and how to provide higher bandwidths. The growing maturity of optical network elements such as OXCs and OADM's will enable optical networks to rapidly provision lightpaths and switch them via wavelength routing. Recently the focus has shifted from pure optical transmissions to optical networking for reducing the cost per connected bit transmitted. The implication of this shift is that the optical layer will move from just providing simple transmission pipes to a more managed and more intelligent optical network. This will allow service providers to deliver a range of new services using such improved optical networks. In order to accomplish this objective successfully, service providers and equipment manufacturers will need to figure out ways to get the highest possible network efficiencies by combining the optical layer with higher layers, e.g. Asynchronous Transfer Mode (ATM), IP/MPLS layers.

2.2.1 The Evolution of the Protocol Stack for the Next-generation Network

It may be noted that many of current transport networks used by the telecom operators have tended to become rather complex in nature. In typical extreme cases, these transport networks contain an ATM layer supported by a Synchronous Digital

Fig. 2.4 Development for IP/MPLS over WDM solutions

Hierarchy (SDH) network that in turn runs on top of a WDM layer. The popularity of the exponentially growing Internet has also created a new market for the so-called Internet Service Providers (ISPs). Telecom operators starting up their own ISP activities tend to keep their transport networks as they are at present and simply run their Internet Protocol (IP) network in parallel with their Public Switched Telephone Network (PSTN), resulting in a typical IP/ATM/SDH/WDM mapping as shown in

Fig. 2.4. The high overhead of ATM (cell tax) and the complexity of the ATM control plane, as well as the need for higher granularities between IP routers make the ATM layer unnecessary. Instead, in order to implement the advantages of traffic engineering functions in the transport network, the IP layer may be empowered with the addition of the Multi-Protocol Label Switching (MPLS) technique as this will allow the setting up of Label Switched Paths (LSPs) through the IP network.

It also appears that, in general, the growth in IP traffic will increase further over the coming years. Even if interconnecting IP routers with dedicated SDH links at data rates of 600 Mbps (i.e. as virtual container level 4 (VC-4)) seems sufficient today, higher bit rates will be required for this very soon. An SDH network may be able to

cope with this requirement in the short term, by leasing concatenated VC-4s. However, on a somewhat longer time scale, a whole wavelength (2.5, 10 or even up to 40 Gbps) may become the appropriate granularity for the direct interconnection of two IP routers. Digital Cross-Connects (DXCs) in SDH can no longer cope with this switching granularity, and the optical layer seems to be the right place to cross-connect these signals. The technology for building Optical Cross-Connects (OXC)s has now become mature enough to become commercialized [25].

By pushing the cross-connecting functionality into the optical layer, a real WDM network is obtained. Therefore we end up with a next generation network, where IP is directly supported by a WDM network. Thus, we will probably evolve from a complex IP/ATM/SDH/WDM multilayered network scenario, towards a simpler MPLS-empowered-IP-directly over WDM network [26]. Moreover, it appears to be almost conclusive that IP will not only rapidly outgrow the existing ATM/SDH infrastructure, but also will take over some of the latter's functions, by converging to become a service integration layer carrying a combined mix of data, voice and video traffic.

2.2.2 Traffic Engineering in IP/MPLS over WDM Network

Fig. 2.5 Network and node architecture for IP/MPLS over WDM networks

A typical IP/MPLS over WDM network and node architecture are shown in Fig. 2.5 (a) and Fig. 2.5 (b) respectively. An OXC is connected to a label switching router (LSR) through a User Network Interface (UNI) and add/drop ports and the LSR is equipped with several transceivers. Traffic originating from the LSR is sent out as an optical signal on one wavelength channel by a transmitter. Traffic destined to the LSR is converted from an optical signal to electronic data by a receiver. The LSRs will be either at the end-nodes or at the intermediate nodes of a label switched path (LSP), and will provide the electrical switching for routing and traffic grooming. A LSR processes all packet traffic flowing through it and ensures the bandwidth demands of the LSP requests on the outgoing lightpaths. Both tunable transceivers and fixed transceivers may be used in a WDM network. The client LSR in the IP/MPLS layer will then request the optical layer for establishing a lightpath through the UNI. Such a two-layer network will have mainly two kinds of the traffic engineering components, i.e. the LSPs in the IP/MPLS layer and the lightpaths in the optical layer.

Fig. 2.6 An example of 32-bit label

Fig. 2.7 Label swapping in the MPLS network

Label Switched Path (LSP)

In the Multi-protocol Label Switching (MPLS) domain, label switching router (LSR) uses a short, fixed-length label inserted in the packet header between the IP packet header and the layer-2 header to forward packets. An example of 32-bit label is shown in Fig. 2.6. It includes four fields, e.g., the label field, the experimental field, the S field and the Time-to-Live (TTL) field [27]. A group of IP packets that are forwarded in the same manner (e.g., over the same path, with the same forwarding treatment) is in the same Forwarding Equivalence Class (FEC). The 20-bit Label field maps the FEC to a corresponding MPLS identifier. The 3-bit experimental field can be used to define different classes of service or per hop behavior for differing classes of traffic within the LSP. The one-bit *S* field represents the last MPLS label contained in the packet. *S* is set to one for the last entry in the label stack (i.e., for the bottom of the

stack) and cleared to zero for all other label stack entries [27]. The final 8 bits of TTL field is analogous to the IP TTL field.

The traffic engineering building blocks in the IP/MPLS layer are the label-switched paths (LSPs). At the ingress LSRs, IP packets are classified and routed based on a combination of the information carried in the IP header of the packets and the local routing information maintained by the LSRs. A corresponding MPLS header is then inserted for each packet between the IP packet header and the level-2 packet header. Within an MPLS-capable domain, an LSR will use the label as the index to switch as specified by the forwarding table entry. The incoming label is replaced by the outgoing label. Before a packet leaves an MPLS domain, its MPLS header is removed. The whole process is shown in Fig. 2.7. The paths between the ingress LSRs and egress LSRs are called label-switched paths (LSPs). An LSP can be set up using an appropriate signaling protocol such as RSVP-TE (Resource Reservation Setup Protocol with Traffic-engineering Extension) [28] or CR-LDP (Constraint Routing Label Distribution Protocol) [29]. With the label switching technology, the routing constraints may be imposed by administrative policies, or by Quality of Service (QoS) requirements. This kind of routing is named as constraint-based routing (CBR). Because the CBR considers more than network topology in computing routes, it may find a longer but lightly loaded path better than the heavily loaded shortest path. Network traffic is hence distributed more evenly. With the CBR, the LSPs can be manipulated not only satisfying QoS constraints but also can reducing costs, balancing network load, or increasing security [30].

Lightpath

The basic mechanism of communication in the optical layer is a *lightpath*. A lightpath [31] is an all-optical path over which data is carried on a single wavelength and may

Fig. 2.8 A example of lightpath in the optical network

span more than one fiber link. Fig. 2.8 gives an example of a lightpath. The electrical signal modulates a laser in the Optical Transmitter (OT), producing an optical signal carried on wavelength λ_1 . If there are other wavelength signals, all the signals may be multiplexed together using the Wavelength Multiplexer (WMUX). Then the multiplexed signal is added into the OXC node A. In Fig. 2.8, it is shown that the wavelength λ_1 traverses three OXC nodes and is dropped at OXC node C. Then the optical signal is demultiplexed and resultant signal wavelength λ_1 is converted to electrical signal by the Optical Receiver (OR). Therefore, a lightpath originating from an OT is switched by OXCs and eventually sinks to an OR. The wavelengths are capable of being dynamically switched inside the optical network by OXCs, which are not sensitive to the signal itself, but only to the wavelength over which it is carried. In

the absence of any wavelength conversion device, a lightpath is required to be on the same wavelength channel throughout its path in the network; this requirement is referred to as the *wavelength continuity* property of the lightpath. This requirement may not be necessary if we also have wavelength converters in the network. A virtual topology [18] of the network will consist of such lightpaths. With a reconfigurable virtual topology, network engineering can maintain the connectivity of the IP/MPLS layer and add more bandwidth wherever the IP/MPLS network gets congested.

2.3 Traffic Grooming

Traffic grooming [7] addresses the gap between the bandwidth capacity of wavelengths and the bandwidth requirement of LSPs. With the improvement of optical technology, the capacity of a single wavelength may reach optical carrier levels (i.e. OC-192 at 10 Gb/s). On the other hand, the bandwidth of an LSP request may be much less, possibly OC-3 (155 Mb/s), or even lower. To make efficient use of the wavelength bandwidth, traffic grooming is needed to effectively pack connections at sub-wavelength granularities onto the wavelength channels. Considerable research on traffic grooming in WDM/SONET rings has been reported in the literature [11-15]. The objective function in these studies is to minimize the total network cost, measured in terms of the number of SONET add/drop multiplexers (ADMs).

Recently, traffic grooming in a WDM mesh network has started to get more attention [7, 16, 17]. In this network, the traffic grooming problem is closely related to the issues of virtual topology design and reconfiguration. Wavelength routing is a major

advantage of a WDM optical network. A wavelength-routed WDM network can provide end-to-end optical communication channels (i.e. lightpaths through optical fibers and intermediate nodes with optical cross-connects), even if the source and destination nodes are not directly connected by a fiber. With the setting up of a lightpath, the two nodes then become virtual neighbors. In a mesh WDM network, there may be a number of connection choices between a node-pair. A lightpath would be an agile way to utilize wavelength resource in the optical layer in such a network. The virtual-topology here would be a set of lightpaths established to provide all-optical connectivity between nodes for a given traffic demand. However, because of scalability and economic concerns, it may not be possible to establish a lightpath for every node pair and some traffic may need to be switched electronically from one lightpath to another at intermediate nodes until it reaches its destination; this approach is called multi-hopping. The processes of setting up individual lightpaths are clearly related to one another since a lightpath may carry multi-hop traffic besides the single-hop traffic between the two nodes it directly connects.

For this reason, the design of the lightpath topology (virtual topology) is a combined problem of optimizing the use of network resources and network throughput, for a given traffic demand. As an example, let us consider a 6-node mesh network topology as shown in Fig. 2.9, assuming that it is a single fiber WDM optical network (one fibre on each span) with each fiber having one wavelength channel. The capacity of each wavelength channel is 2 units of traffic. There are four connection requirements: (A, B), (B, C), (A, C) and (A, D) with each requiring one unit of traffic. There are two different ways of aggregating traffic and assigning lightpath. The first

assignment is shown in Fig. 2.9 (a). Three lightpaths AB, BC and AFEDC are set up and 3 optical transmitters/receivers (Tx's/Rx's) and 6 wavelength-spans (one on each link) are used. Connection request (A, B), (B, C) and (A, C) occupy lightpath

Fig. 2.9 An illustrative example of traffic grooming in WDM optical mesh networks

AB, BC and AFEDC respectively. The connection request (A, D) cannot be fulfilled and has to be blocked. The second solution is to groom the traffic (A, C) into lightpaths AB and BC, as shown in Fig. 2.9 (b). Let (A, B) share the lightpath and the Tx/Rx with (A, C) from A to B. Similarly, let (B, C) share the lightpath and the Tx/Rx with (A, C) from B to C. Now a lightpath AFED can be set up for connection request (A, D). The second solution requires 3 Tx's/Rx's and 5 wavelength-spans and can accept all connection requests. This example shows if we can groom the traffic and establish the lightpath accordingly, not only does the cost of the network get reduced but also greater traffic demands may be accepted in the network.

When the traffic rates between node pairs of a network fluctuate dynamically over time, a virtual topology which is optimized for a given traffic demand (i.e. one which would be a snapshot of the changing traffic matrix at some instant of time) may not be

able to respond efficiently to a different traffic demand. This implies that the virtual topology should also be changed to match changing traffic patterns. The dynamic structure of the optical cross-connects, i.e., the ability of switching wavelength channels from any input fiber to any output fiber dynamically, allows this change in the optical layer. This is known as reconfiguration of the virtual topology or *dynamic traffic grooming*. It may be noted that, by definition, the reconfiguration problem includes the virtual topology design problem. Therefore, it actually amounts to being an optimization problem over several traffic metrics, which needs to be solved on-line, in contrast to static virtual topology design problem.

2.3.1 Static Traffic Grooming in WDM Mesh Networks

For the mesh WDM network, most of the current literature has focused on traffic grooming problem when the node-to-node traffic demands do not vary significantly over time; i.e. when they are well represented by a static matrix of traffic demands. In this case, the virtual topology design problem can be formulated as an optimization problem, using principles from multi-commodity flow for physical routing of lightpaths and traffic flow on the virtual topology. In general, the optimal virtual topology problem has been conjectured to be NP-hard [7], which means that the problem cannot be solved optimally for large problem sizes.

In [32], the problem of logical topology design is formulated as a mixed integer linear programming (MILP) problem but the number of wavelengths the fiber supports is not a constraint. The drawback in this approach is that the physical topology becomes irrelevant for designing a logical topology.

In [16] the authors formulated the logical topology design problem as a nonlinear optimization problem. The objective considered was either delay minimization or minimizing the maximum offered load. The authors subdivide the problem into four sub-problems. These are: (1) determining a logical topology (logical links), (2) routing the logical links over physical links, (3) assigning wavelengths to the routes, and (4) routing packet traffic on the logical topology. The authors only consider sub-problems (1) and (4). Simulated annealing (which is NP-hard) has been used to solve sub-problem (1) and flow deviation has been used to solve sub-problem (4). The drawback of the above approach is that the simulated annealing approach will be computationally very expensive for large networks.

In [17] the authors presented an exact integer linear programming (ILP) formulation for the complete virtual topology design, including choice of the constituent lightpaths, routes for these lightpaths, and intensity of packet flows through these lightpaths. By minimizing the average packet hop distance in the given objective function and by relaxing the wavelength-continuity constraints (i.e., assuming wavelength converters at all nodes), it is demonstrated that the entire optical network design problem can be considerably simplified and made computationally tractable. Although an integer linear programming (ILP) may take an exponential amount of time to obtain an exact optimal solution, high quality solutions can be obtained in the first few iterations of the branch-and-bound method [17].

In [7], the authors designed the virtual topology under the restriction that a traffic flow will not be split. A set of traffic matrices is given. Each traffic matrix in the traffic-

matrix set represents one particular group of low-speed connection requests between the nodes of the network. For example, there may be four traffic matrices: an OC-1 traffic matrix, an OC-3 traffic matrix, an OC-12 traffic matrix, and an OC-48 traffic matrix. In an OC- n traffic matrix, where n can be chosen as 1, 3, 12, 48, the element is chosen as integer and denotes the number of OC- n traffic flows from certain source node to certain destination node. An OC- n traffic flow cannot be split between different paths. An ILP formulation is presented and two heuristics are proposed and evaluated where the objective is to maximizing total throughput.

In [33], the authors present a general linear formulation which considers routing traffic demands, and routing and assigning wavelengths to lightpaths, as a combined optimization problem. The objective is to minimize congestion. It is shown that the linear formulation for small networks can be solved in reasonable time. For large networks, the authors solved the linear formulation by relaxing the integer constraints. Since the whole problem is linearizable, the solution obtained by relaxation of the integer constraints yields a lower bound on congestion. This is useful in comparing with the efficiency of proposed heuristic algorithm.

Besides calculating an optimum virtual topology under a given traffic matrix, the reconfiguration of virtual topology was also studied in [17, 18]. In [17, 18], the authors used the ILP formulation to derive new virtual topologies from existing virtual topologies under the assumption that the traffic distribution will not change fast. The objective is to minimize the reconfiguration from old virtual topology to the new virtual topology. Because solving an ILP problem is time consuming and only

suitable for small networks, a heuristic algorithm was proposed in [18]. The authors in [18] introduced high and low watermark parameters on lightpath loads to detect any overutilized or underutilized lightpaths, and to trigger an adaptation step. The lightpath additions and deletions were examined under dynamic traffic model. However, the important performance parameter of blocking ratio or throughput was not considered there.

2.3.2 Dynamic Traffic Grooming in WDM Mesh networks

The explosive growth of the Internet has led to a situation where the traffic offered no longer matches that in a typical static state (i.e., a “semi-permanent” one) of the transport network. As applications such as peer to peer, video on demand, video conferencing and etc. increase, the traffic will become bursty and randomly generated in space. It would not be acceptable anymore for an Internet Service Provider (ISP), to launch a new request to its carrier for another bandwidth provisioning, before the previous request is actually treated and realized by the latter. Therefore, an important requirement for next-generation transport networks would be greater flexibility by providing automatically switched leased line services. This is currently an important issue of interest in major standardization bodies. ITU-T is setting up an Automatically Switched Optical Network (ASON) architecture in the recommendation Global. Automatically Switched Transport Network (G.ASTN) [34]. The Optical Internetworking Forum (OIF) is also specifying the UNI between the transport network and its clients [35]. The Internet Engineering Task Force (IETF) is studying how to adopt IP/MPLS protocols in the WDM network for the implementation of the switching functionality of the WDM network [36].

With the increasing maturity of automatically switched leased line services, bandwidth will have to be provided immediately according to the users' requests. This will trigger many new applications that are not there today and lead to much higher bandwidth consumptions in the future. Recently, there has been increasing interest in changing the virtual topology dynamically according to traffic changes in the IP/MPLS layer [10, 20, 37-39]. For a traffic load change in the IP/MPLS layer, dynamic traffic grooming will decide whether or not to change the virtual topology and how the change is to be made in order to alleviate congestion and efficiently operate the overall networks. In this situation, on-line algorithms are necessary and system restriction need to be considered.

2.3.2.1 Interconnection Models

Based on the relationship between the control planes of the IP/MPLS and optical layers, the architecture of IP/MPLS over optical networks is generally classified into three interconnection models - namely the overlay model, the augmented model and the peer model [40]. Of these, the overlay and the peer models are well defined and researched and are illustrated in Fig. 2.10 and Fig. 2.11, respectively. The peer model has a single integrated control plane which controls both the optical network and its client (IP/MPLS) network. When there is a single network involved and both the IP/MPLS and optical domains belong to the same entity, then a common Interior Gateway Protocol (IGP) such as Open Shortest Path First (OSPF), with appropriate extensions, can be used to distribute topology information [41] over the integrated IP-

optical network. An assumption is that a common addressing scheme will be used for both the optical and IP/MPLS networks. A common address space can be easily realized by using IP addresses in both the IP/MPLS and optical domains where the optical network elements become IP addressable entities as noted in [42]. Under this model, integrated routing can be employed. This approach permits a router to compute an end-to-end path to another router across the optical network.

On the contrary, in the overlay model, the optical networks and its client IP/MPLS networks will have strictly separated and independent control planes. The IP/MPLS layer routing, topology distribution and signaling protocols are independent of the routing, topology distribution, and signaling protocols within the optical domain. Only limited information regarding the optical network is shared with IP/MPLS client devices. The IP/MPLS client devices will have no knowledge of the optical topology or resource information. A separate instance of the control plane (especially the routing and signaling protocols) would have to be deployed in the optical domain, independent of what exists in the IP/MPLS domain. Compared to the peer model, the overlay model has several advantages. First, it only needs a limited interaction between both control planes (e.g., request for the set-up of a connection) through the UNI as shown in Fig. 2.11. Second, in practice, separate management for each network layer may be preferred to keep the network information independent of each layer. It supports multiple clients on the same optical transport network and facilitates a smooth migration with existing optical transport network infrastructure and services. Third, in the overlay model, the privacy of each layer can be easily ensured. In the

short term, the overlay model seems to be more realistic and feasible and has been experimented with extensively in laboratories and research projects [43].

Fig. 2.10 The network architecture of peer model

Fig. 2.11 The network architecture of overlay model

2.3.2.2 Dynamic Traffic Grooming Policies in the IP/MPLS over WDM Networks

Dynamic traffic grooming in the IP/MPLS over WDM network becomes a two-layer routing problem regarding the constraints in the IP/MPLS and the optical layers and the relationship between them. In the IP/MPLS layer, MPLS traffic engineering can try to distribute traffic evenly in the network so as to exploit network resources better and to minimize congestion [44]. In the optical layer, wavelength routing needs to consider the wavelength continuity constraint (if wavelength conversion capability is not incorporated in the optical network) and the availability of add/drop ports. Several routing methods and wavelength assignment methods have been studied in the past few years [45].

Some early work on dynamic traffic grooming was reported in [8-10, 37, 39, 46]. A few analytical models, using Markov processes, have also been proposed to study the performance of different traffic grooming strategies under dynamic traffic conditions. However, heuristic approaches have been popularly used to maximize the number of admitted calls, or to minimize the blocking probabilities, given a specific resource set.

The traffic grooming policy can be divided into two categories based on the network connection architecture: the overlay model and the peer model. In the peer model, the network manager can utilize the link usage information in both the IP/MPLS and optical layers to calculate paths. In the overlay model, the optical layer is not visible from the IP/MPLS layer. The IP/MPLS layer has to request for a lightpath connection through the UNI for new bandwidth. However, this may encounter blocking even

there is idle wavelength resource in the optical layer because the connection request does not consider the topology in the optical layer. The blocking performances of the overlay and peer models were compared in [38]. The results show that a network operated with the peer model will find more feasible paths between the end-nodes than a network using the overlay model and will consequently suffers less blocking.

In [47], a maximum open capacity routing algorithm (MOCA) was proposed under the peer model. MOCA always selects a route for the current LSP request so that the residual capacities between the source and the destination are maximized. MOCA is complicated because the maximum flow values for all the node pairs have to be computed in order to set the cost for each link. This would be undesirable in an online traffic engineering system where connection requests have to be met as quickly as possible.

A novel graph model was introduced under the peer model in [8]. Considering a heterogeneous WDM mesh network environment, the authors captured the different abstract layers in the network with the help of a single auxiliary graph. The presence of certain equipment or functionality at a node was represented by the edges to (from) that node. The novel feature of the auxiliary graph was that different objective functions under different grooming policies could be represented by weighting the edges according to the corresponding physical constraints. The model can be applied to both static and dynamic traffic grooming. In static grooming, the traffic selection scheme is the key to achieve good network performance. The dynamic grooming problem becomes an integrated routing problem when the edges in the auxiliary graph

are given different weights. Four fixed traffic grooming policies and an adaptive traffic grooming policy have been suggested based on the auxiliary graph in [39].

The work presented by the same authors in [9] also uses the same concept of auxiliary graph; however, they considered different grooming OXC architectures. They presented four such architectures: (1) single-hop grooming OXC, which can switch only at wavelength granularity (2) multi-hop partial-grooming OXC, which can switch at wavelength granularity using a wavelength-switch fabric, and also switch few, but not all, of the wavelength channels at sub-wavelength granularity, (3) multi-hop full-grooming OXC, which can switch all the wavelength channels at sub-wavelength granularity, and (4) light-tree-based source-grooming OXC, which has the capability to duplicate the traffic from one input port to multiple output ports. They also presented two algorithms to perform grooming using auxiliary graph, and compared the network performance of each type of OXCs.

Even though the peer model can facilitate the network optimization, the overlay model has attracted increasing attention for its practicality and ease of implementation. In [10], the authors proposed the *IP-Layer-First* (ILF) and *Optical-Layer-First* (OLF) under the overlay model for the establishment of LSPs. With the ILF policy, networks first try to route a new LSP request in the IP/MPLS layer. Only when this does not have enough bandwidth, the LSP request is transferred to the optical layer for setting up a new lightpath directly between the source and destination. In contrast, with the OLF policy, the network first attempts to set up a lightpath for a new LSP request in the optical layer.

The authors in [20] proposed an algorithm for establishment of lightpaths whereby a lightpath is set up if the remaining capacity of every lightpath is less than a threshold Q . The blocking performance of the network is improved with the increase in the value of Q . It can be shown that the algorithm becomes the OLF policy when the value of Q is equal to the bandwidth of the lightpath.

In [46], a lightpath is set up whenever a feasible one-electrical-hop path cannot be found for a new LSP request in the existing IP topology. This policy is called the One-Hop-First (OHF) policy. The OLF and OHF policies result in less blocking than the ILF, as they tend to set up new lightpaths before blocking happens in the IP layer. In contrast, when the ILF policy triggers a new lightpath to be set up, the IP layer would already be congested with a lot of traffic flowing on inordinately long routes.

2.4 Summary

The enabling technologies in optical networks are reviewed in this chapter. The basic concepts in the IP/MPLS over WDM network relating traffic grooming are described. There are mainly two traffic engineering entities in the IP/MPLS over WDM networks, e.g. the LSP and the lightpath. For easy understanding of the IP/MPLS over WDM network, we have also reviewed the evolution of the protocol stack for the next-generation network.

Traffic grooming is important to efficiently operate IP/MPLS over WDM networks. We have reviewed two types of traffic grooming, e.g. static traffic grooming and

dynamic traffic grooming. Because static traffic grooming can be done offline, the optimization method for traditional multi-commodity problem can be used. Future network will be data centric. The traffic will be bursty and randomly generated in space and time. Dynamic traffic grooming is important to cope with such kind of traffic. For dynamic traffic grooming, the algorithm must consider the system constraints and be fast enough for on-line implementation. Several traffic grooming policies have been reviewed.

Although considerable works have been done for dynamic traffic grooming, none of them cater to the needs of traffic grooming under dynamic conditions where responses are adaptive to the level of congestion in the network. In this work, we will develop efficient dynamic traffic grooming methods considering both optical and IP layers' characteristics for significantly reducing LSP blocking ratio and providing differentiated service for different classes of traffic. We will also develop traffic grooming methods to handle multicast traffic in IP/MPLS over WDM networks.

Chapter 3 The Path Inflation Control Policy

3.1 Introduction

IP/MPLS over WDM is expected to be the technology dominating the next phase of Internet expansion. For the IP layer, multiprotocol label switching (MPLS) using label switched paths (LSP) will provide traffic engineering capabilities and QoS control for carrier networks. In the future WDM network, a lightpath can be established between two nodes by configuring the transmitter, receiver and intermediate optical crossconnects (OXC) along the path for a one-electrical hop communication channel with a large bandwidth [18, 31]. A virtual topology [18] of the network will consist of such lightpaths. Since this virtual topology will be reconfigurable, traffic engineering can provide bandwidth as per the traffic distribution in the upper layers.

In an IP/MPLS over WDM network, the LSP connection demands from the IP networks not only have significantly lower capacity requirements than the bandwidth of the wavelength channels, but may also require different bandwidth granularities depending on the application being considered. The bandwidth guaranteed LSP traffic flows need to be efficiently multiplexed, or “groomed,” on to the wavelength channels in order to efficiently operate the overall network [18]. In our subsequent discussions, we denote by $r_i^{s,d}$ the i^{th} LSP request from node s to d .

Earlier works on traffic grooming have mostly focused on SDH/SONET rings [11].

This is appropriate since current backbone transport infrastructures are generally arranged as rings. As optical fiber systems evolve from transmission to networking [48], increasing amounts of research efforts have been conducted on the traffic-grooming problem in optical WDM mesh networks. Under the static traffic model, the traffic-grooming problem in WDM mesh networks is formulated in [7] as an integer linear program (ILP) to maximize the network throughput for a given traffic demand matrix and given network resource. Based on the observation of the results from the ILP solutions, two heuristic algorithms were also proposed and compared. A generic graph model was proposed to accommodate different optimizing objectives by varying the weights of different parts of the WDM mesh networks in [8]. The authors in [49] studied the effects of varying the costs of wavelength links, the wavelength routing ports and the sub-wavelength routing port on the routing decisions made in IP/MPLS over WDM networks. An analytical model for single hop traffic grooming in mesh WDM optical networks was developed in [37].

Since the lightpath will be dynamically set up in future optical networks, emerging new applications and services such as “bandwidth on demand” and “bandwidth trading” will require the network to respond dynamically to mostly unpredictable traffic demands [20]. In this context, dynamic traffic grooming in meshed WDM networks has attracted considerable attention as in [20, 39]. In this situation, the virtual topology needs to be reconfigured dynamically according to the traffic changes in the IP/MPLS layer. For service providers, it would be important to establish the new lightpaths in a way such that the overall network performance is optimized at the minimal cost.

Fig. 3.1 Congestion in IP/MPLS over WDM Networks

It may be noted that under the MPLS protocol, traffic flows are routed as per the network link state using explicit routing [29]. As an example, consider the situation in Fig. 3.1 (a) where the k^{th} LSP request from node 1 to node 2, i.e., $r_k^{1,2}$, arrives in the network when link (1, 2) is congested, but when links (1, 3) and (3, 2) can still provide the bandwidth required by $r_k^{1,2}$ if the alternate path 1-3-2 is used. However, as this kind of alternate routing increases, link (3,2) may eventually get congested. LSP requests from node 3 to 2 may then be forced to use the alternate path 3-4-2. As shown in this simple example, congestion in one link may progressively cause other links to get congested in the IP layer and the routing efficiency and performance of the whole network will get degraded.

Minimizing congestion is a central goal of traffic engineering [44]. In the telephone network, trunk reservation [21] allow a link to reject alternatively routed calls if the number of idle circuits on the link is less than or equal to the trunk reservation parameter. This kind of alternative routing can improve the efficiency of the telephone network. However, since LSP requests do not have fixed bandwidths like telephone circuits, it is difficult to define an analogous reservation parameter for the IP/MPLS over WDM case.

An alternative would be to dynamically set up a new lightpath to provide bandwidth for a link with congestion in the IP/MPLS layer, before its congestion spreads to other links. From this point of view, dynamically setting up lightpaths is important to solve the congestion problem in IP/MPLS over WDM networks. This has been shown in Fig. 3.1 (b). For this, we first need to evaluate the extent of congestion and then decide when to set up a new lightpath and how this should be done.

For the IP/MPLS over WDM optical network, we consider here an overlay routing model. The network model is shown in Fig. 2.10, where the IP/MPLS layer and the optical layer operate independently for routing and signaling functions. For the overlay model, the *IP-Layer-First* (ILF) and *Optical-Layer-First* (OLF) policies were proposed for the establishment of LSPs in [10]. The networks with the ILF policy generate the request to set up a lightpath between end nodes only when an LSP request is blocked in the existing IP topology. In contrast, in the OLF policy, networks first transfer the LSP request to optical layer for setting up a lightpath even if there is enough bandwidth in the IP/MPLS layer. In [46], the authors proposed the One-Hop-First (OHF) policy that tries to set up a lightpath whenever a feasible one-electrical-hop path cannot be found for a new LSP request in the existing IP topology.

It is shown that the ILF policy has the highest blocking ratio among the three policies [10] [46]. This is because, when the ILF policy tries to set up a new lightpath, the IP/MPLS layer is already congested with a lot of its traffic flowing on inordinately long paths. The OLF and OHF policies achieve better performance because they trigger a lightpath establishment before blocking happens in the IP/MPLS layer. This

may avoid the congestion spread. However, the optical resource, e.g. wavelengths and transceivers, is limited. We cannot set up as many lightpath as we want. Monitoring the congestion level in the IP/MPLS layer and set up a new lightpath only when it is needed will make the network resource efficiently used and improve the overall networks. This is attempted by the PIC strategy that is proposed here.

The rest of this chapter is organized as follows. Section 2 gives the network models and traffic models used in this chapter. The routing methods in the IP layer and in the optical layer are given in Section 3. The key ideas of the Path Inflation Control (PIC) Policy are introduced in Section 4. In Section 5, the PIC policy is studied and compared using simulations with other two LSP control policies. The summary is given in Section 6.

3.2 Network and Traffic Models

The physical topology $G_p(V, E_p)$ in the optical layer is the interconnection of fibers and OXCs. Here, V is a set of N nodes and E_p is a set of F fiber links where each link is assumed to be of unit length. We define $D^{s,d}$ as the length of the shortest path (i.e. number of fiber links) between nodes s and d . Each link has $2W$ wavelengths, with W in each direction. We only consider unidirectional light paths in this chapter. Fig. 2.5 (b) shows the structure of a typical node in an IP/MPLS over WDM network [10]. An OXC is connected to a LSR through a User Network Interface (UNI) and add/drop ports. Previous studies have shown that providing full wavelength conversion capabilities at all nodes is not really required [50, 51]. These show that having a few nodes with even partial conversion capabilities performs almost as well as a system

where all nodes are capable of doing full conversion. In this paper, we have assumed for simplicity that all OXCs are capable of full wavelength conversion. The approaches proposed by us can however be extended to systems with partial or sparse conversion capabilities.

The LSRs can be either at the end-nodes or at the intermediate nodes of an LSP, and provide the electrical switching for routing and traffic grooming. A LSR processes all packet traffic flowing through it and ensures the bandwidth demands of the LSP requests on outgoing lightpaths. It is assumed that the LSP requests to the overall network come from a Poisson process with average rate λ and have random exponentially distributed holding times with mean μ . We consider arbitrary bandwidth traffic flows rather than discrete time-division multiplexing (TDM) circuits where $b_i^{s,d}$ is the bandwidth requested by $r_i^{s,d}$, the i^{th} LSR request between the end nodes s and d . We model this to be a random variable uniformly distributed in $[x_1C, x_2C]$, where C is the capacity per wavelength channel and $0 < x_1 \leq x_2 \leq 1$. In the simulation models, the end nodes of an LSP request are also randomly selected. The traffic generated per node is normalized to the channel capacity C , and is given by

$$\rho = \frac{(x_1 + x_2)}{2N} \lambda \mu \quad (\text{Erlangs}) \quad (3.1)$$

The *LSP Request Blocking Ratio* P_b is given by

$$P_b = 1 - \frac{\sum_s \sum_d \sum_i b_i^{s,d} x_i^{s,d}}{\sum_s \sum_d \sum_i b_i^{s,d}} \quad (3.2)$$

where $x_i^{s,d} = 1$ only if $r_i^{s,d}$ has been routed in the network and is 0 if it was blocked.

In this work, we compare different traffic grooming policies according to the LSP request blocking ratio. The best policy should decrease the LSP request blocking ratio fastest as the normalized traffic load decreases.

The number of transceivers is equal to the number of add/drop ports at each node. Since this determines the main cost of the node, it would be important to keep the total number of transmitters and receivers low in order to do traffic grooming economically in IP/MPLS over WDM networks. For a measure of this, we define the *Add/Drop Ratio* R as in [10]

$$R = \frac{T_R}{W} \quad (3.3)$$

where T_R is the number of transmitter/receivers per fiber and W is the number of wavelength per fiber.

In this thesis, we consider a centralized approach to the traffic-grooming problem. An implicit assumption here is that the inter-arrival time for LSP requests is typically much longer than the time it takes for control signals to propagate from the various nodes to the central manager or for request signals to go from the IP/MPLS layer to the optical layer. Therefore, a central manager in each layer will collect the link usage information from routers or OXCs and update the topology changes before next connection request comes. The Dijkstra algorithm will be applied to calculate a shortest path based on an updated topology in both layers.

3.3 Routing in the IP/MPLS and Optical layers

3.3.1 Routing in the Optical Layer

We assume that all the OXCs in the optical layer are wavelength convertible over all wavelengths. This implies that with an idle transmitter and an idle receiver at nodes m and n respectively, a light path between these nodes can always be set up as long as a path with at least one idle wavelength (possibly different for different links) on all its links can be found between them. The optical layer becomes a circuit switched network. In this chapter, we use two routing methods in the optical layer. The first is the alternate shortest path routing (ASPR) method [52]. The second is the trunk reservation routing (TRR) method [21].

It is shown that the ASPR algorithm can achieve lower blocking ratio than the shortest routing algorithm [53]. Let $w^{m,n}$ be the number of idle wavelengths for a directed link from node m to node n . Let $A = [a_{mn}]$ be a $N \times N$ matrix representing the dynamic topology of the optical layer where the elements of matrix A are as follows -

$$a_{mn} = \begin{cases} 1 & \text{for } 1 \leq w^{m,n} \leq W \text{ and } m \neq n \\ \infty & \text{otherwise} \end{cases} \quad (3.4)$$

For setting up a new lightpath between two nodes in this dynamic topology, the *Dijkstra* algorithm [54] is applied to find paths between them.

As noted before, using alternate routing will cause congestion to spread in the optical layer. The traditional TRR method [21, 55] can deal with such congestion-spread

problem. We define the alternate lightpath (AL) between node s and d in the optical layer as the path whose length $H^{s,d}$ is larger than $D^{s,d}$. The lightpath whose length is equal to $D^{s,d}$ is absolutely shortest lightpath (ASL). If a connection request uses an AL in the optical layer, then the TRR method will use the dynamic topology as $A' = [a'_{mn}]$.

$$a'_{mn} = \begin{cases} 1 & \text{for } \alpha < w^{m,n} \leq W \text{ and } m \neq n \\ \infty & \text{otherwise} \end{cases} \quad (3.5)$$

where α is a trunk reservation parameter and chosen integer value of ($\alpha \geq 1$). It may be noted that here α wavelengths will be reserved for absolutely shortest lightpath (ASL). The trunk reservation method will use the *Dijkstra* algorithm based on dynamic topology A' to calculate a path from node s to d if an AL has to be used. It is noted that a path may be found in A while no path from s to d in A' can be found. The TRR method becomes ASPR method when $\alpha = 0$. The flow chart of TRR method is given in Fig. 3.2.

Fig. 3.2 The flow chart of trunk reservation routing method in the optical layer

It is assumed that a lightpath is torn down immediately whenever it is empty and its wavelength links are released. The link state information in the optical layer and IP layer is immediately updated whenever a lightpath is set up or torn down.

3.3.2 Routing in the IP Layer

For this type of routing, consider a new LSP request $r_i^{s,d}$ as the i^{th} request between nodes s and d requesting bandwidth $b_i^{s,d}$. For this, lightpaths with residual bandwidths larger than or equal to $b_i^{s,d}$ are considered to be *feasible lightpaths*. The *feasible*

virtual topology in the IP/MPLS layer is represented by the $N \times N$ matrix $V = [v_{mn}]$ whose elements are given by

$$v_{mn} = \begin{cases} \min_{1 \leq q \leq k} H_q^{m,n}(b_i^{s,d}) & k > 0 \\ \infty & k = 0 \end{cases} \quad (3.6)$$

Here k is the number of feasible lightpaths from node m to n at time t and $H_q^{m,n}(b_i^{s,d})$ is the length (number of fiber links) of the q^{th} feasible lightpath (with bandwidth larger than or equal to $b_i^{s,d}$) from node m to n at time t . This feasible virtual topology V is used to compute the shortest path for a new LSP request where a tie, if any, is resolved in favor of the path with the minimum number of lightpaths. This shortest path is then used as the *feasible path* (FP) for the LSP request.

It may be noted that an assumption typically made is that a particular traffic flow cannot be split between multiple paths. This has also been assumed in this thesis. Here, once a FP is found, the LSP request is routed on the narrowest, shortest feasible lightpaths as follows. If more than one feasible lightpaths exists between a node pair along the feasible path, the shortest one is chosen and a tie here is resolved in favor of the one with the smallest residual bandwidth. If an LSP request is routed in the network or an LSP request gets terminated, the link state data in the IP/MPLS layer is immediately updated.

3.4 Path Inflation Control Policy

In the IP/MPLS layer, there would be two kinds of paths between any node pair s and d . We define the *absolute shortest path* (ASP) as the shortest possible path (in terms

of the number of fiber links) in the original network topology and assume this to be of length $D^{s,d}$ between nodes s and d . (One may have multiple ASPs between s and d but then these would all be of the same length.) The other paths between s and d would be alternate paths (APs) that are longer than the ASP. If a new LSP request needs more bandwidth than what is available on the ASP from s to d , then it would have to be routed along an AP. Let $l_i^{s,d}$ be the length of the FP calculated for the LSP request $r_i^{s,d}$. As $l_i^{s,d} \geq D^{s,d}$, it may be seen that as traffic load and this kind of alternate routing increase, the average weighted length of LSPs from node s to d will also increase, further increasing the congestion in the network. We propose to measure the degree of congestion from node s to d at time t by a Path Inflation Index (PII) parameter $L_t^{s,d}$, which is defined as-

$$L_t^{s,d} = \frac{\sum_i l_i^{s,d} b_i^{s,d} x_{i,t}^{s,d}}{\sum_i b_i^{s,d} x_{i,t}^{s,d}} \quad (3.7)$$

where the variable $x_{i,t}^{s,d}$ is 1 if $r_i^{s,d}$ is present in the network at time t , and is 0 otherwise.

It is the average weighted length of LSP from node s to d at time t . $L_t^{s,d}$ is equal to 1 when only ASPs are used for routing between s and d , but exceeds 1 when APs are also used.

Typically, we would like to allow some alternate routing between s and d in order to reduce blocking, as long as the excessive use of APs does not lead to more congestion and blocking for traffic between other node pairs. The proposed PIC policy uses a preset threshold β ($\beta \geq 1$) to tackle this. New LSP requests between nodes s and d are

discouraged from using existing APs if this will make $L_t^{s,d} > \beta D^{s,d}$. To the extent possible, it would be more desirable in this case to set up and use a new lightpath for the new LSP request between s and d . It may also be noted that this proposed PIC policy becomes the ILF policy as the value of β goes to infinity.

For the PIC policy proposed here, if $r_k^{s,d}$ arrives in the network at time t and a feasible path of length $l_k^{s,d}$ for it can be found in the current IP topology, then a tentative value for the PII is first calculated as

$$L_t^{s,d}(\text{new}) = \frac{\sum_i l_i^{s,d} b_i^{s,d} x_{i,t}^{s,d} + l_k^{s,d} b_k^{s,d}}{\sum_i b_i^{s,d} x_{i,t}^{s,d} + b_k^{s,d}} \quad (3.8)$$

This is used in our proposed PIC policy to route the new LSP request from s to d and to decide if a new lightpath is to be set up for this.

In the IP/MPLS over WDM network, we consider two situations in which a lightpath establishment needs to be triggered. The first situation happens when $L_t^{s,d} > \beta D^{s,d}$. Setting up a lightpath with length restriction of $\beta D^{s,d}$ and routing the LSP request in the shorter path can avoid the PII value increasing beyond $\beta D^{s,d}$ and the consequent spreading of congestion. We denote this situation as *Situation 1*. It may also be noted that if $l_k^{s,d} \leq \beta D^{s,d}$, then lightpath establishment will not be triggered as *Situation 1* cannot arise from routing this LSP request. Taking this into account, the condition of the *Situation 1* becomes ($L_t^{s,d} > \beta D^{s,d}$ and $l_k^{s,d} > \beta D^{s,d}$). The second situation happens when the IP/MPLS layer does not have enough bandwidth to accommodate a new

LSP request. We denote this situation as *Situation 2*. In this case, to maintain the connectivity of the IP/MPLS layer, a lightpath will have to be set up in the optical layer. It may be noted that an LSP request in this situation will be blocked if such a lightpath cannot be set up.

Based on the combination of different lightpath establishment strategies, we propose three PIC policies. In the PIC 1 policy, we use the ASPR method to calculate lightpaths in both *Situation 1* and *Situation 2*. It is noted that the lightpath in *Situation 1* should be shorter than or equal to $\beta D^{s,d}$, but there is no restriction on the lightpath length in *Situation 2*. In the PIC 2 policy, the optical layer will try to control the congestion spread using the TRR method. If an AL needs to be used in the optical layer, we use the trunk reservation method to calculate a lightpath in both situations. In the PIC 3 policy, we use the ASPR method (relax trunk reservation parameter to 0) for *Situation 2* in PIC 2 policy. This is done considering the importance of maintaining connectivity for the IP/MPLS layer. The flow charts for the three traffic-grooming policies are given in Fig. 3.3, Fig. 3.4 and Fig. 3.5, respectively.

Fig. 3.3 Flow chart of PIC 1 policy

Fig. 3.4 Flow chart of PIC 2 policy

Fig. 3.5 Flow chart of PIC 3 policy

3.5 Performance of the Proposed PIC Policy

Fig. 3.6 The NSF network topology

Fig. 3.7 The COST239 network topology

We use simulations to study the performance of our proposed PIC policies. These have been carried out for the typical NSF network with 14 nodes and 21 links shown in Fig. 3.6 and the COST239 network with 11 nodes and 26 links shown in **Fig. 3.7**. The degree of a node in a graph is the number of edges joined to it. The average node degree in the NSF network and COST239 network are 3 and 4.72 respectively. The average hop distances between nodes in the two topologies are 2.14 and 1.56 respectively. The COST239 network has higher average node degree and shorter average node distance than NSF network. Hence, the NSF network is sparser than COST239 network or, alternatively, the COST239 network is denser than the NSF network. If the average length of lightpath in a network is denoted by H_p , the maximum number of lightpaths that can be supported in the network is estimated as by $2FW/H_p$ in [17]. Here, F is the number of links in the network and W is the number of wavelengths in a fibre. So the NSF network can support maximum $\lfloor 2 \times 21W / 2.14 \rfloor = \lfloor 19.63W \rfloor$ lightpaths and the COST239 network $\lfloor 2 \times 26W / 1.56 \rfloor = \lfloor 33.33W \rfloor$ lightpaths. The COST239 network can accept more

connection requests than the NSF network under the same blocking ratio if every link has the same number of wavelengths. For this reason, we use different traffic intensity to examine different networks. For both networks, we assume that each link has $W = 8$ wavelengths in each direction, and that the capacity of each wavelength is taken to be unity. In this work, we consider that the bandwidths of LSP requests are uniformly distributed in $[0.05, 0.4]$ and the end nodes of LSP requests are randomly selected in the network. For the results reported here, every simulation run has been repeated 10 times with 1,000,000 LSP requests for every run, and results have been averaged. We have also obtained 95% confidence intervals for our results and show them in the figures.

We first examine the effect of the β value on the network performance under the PIC 1 policy. The simulation results are given in Fig. 3.8 and Fig. 3.9 for the NSF network and the COST239 network, respectively. Three different traffic loads are used, such that their lowest LSP request-blocking ratios are close to approximately 10^{-2} , 10^{-3} and 10^{-4} . As expected, it was shown that the COST239 network can accommodate more traffic than the NSF network under the same blocking ratio value. This is because the COST239 network has richer connections and smaller average node distance than the NSF network. Such effect has been studied in [56]. In the NSF network, as β increases from 1 with sufficiently high traffic loads, the LSP blocking ratio will first decrease (since more alternate paths may be used) but will subsequently increase (because of increasing congestion from the use of alternate paths). In the COST 239 network, the blocking ratio will continuously increase as β increases from the value of 1.

In terms of overall performance over a broad traffic range, the best choice here appears to be $\beta = 1.4$ for the NSF topology and $\beta = 1$ for the COST 239 topology. It seems that the COST239 network is more likely to use ASPs. This is caused by the topology difference between the NSF network and the COST239 network. The congestion will be most likely spread in the network whose average distance is small.

Fig. 3.8 Blocking ratio vs. the β value under the PIC 1 in the NSF network

Fig. 3.9 Blocking ratio vs. the β value under the PIC 1 in the COST 239 network

The alternate routing in the optical layer may also cause the problem of spreading congestion. We have introduced the trunk reservation method into PIC 1 policy to control congestion in the optical layer[55]. This policy is named as PIC 2 policy. It may be noted that the PIC 2 policy becomes the PIC 1 policy when trunk reservation parameter $\alpha = 0$. The effect of trunk reservation parameter on the network performance under the PIC 2 policy is given in Fig. 3.10 and Fig. 3.11 for NSF and COST239 network respectively. In the PIC 2 policy, the trunk reservation parameter α can be 1, 2, 3, 4, 5, 6, 7 and 8. Here we use the optimum β value of 1.4 and 1 for the NSF network and the COST239 network, respectively. It is noted that with $\beta = 1$, both PIC 2 and PIC 1 policies only set up absolutely shortest lightpath in situation 1.

Fig. 3.10 Blocking ratio vs. TR parameter α under the PIC 2 in the NSF network

Fig. 3.11 Blocking ratio vs. TR parameter α under the PIC 2 in the COST 239 network

To our surprise, it is found that the PIC 1 policy (PIC 2 policy with $\alpha = 0$) has almost the same blocking performance as the PIC 2 policy ($1 \leq \alpha \leq 8$) when traffic load is heavy, and outperforms the PIC 2 policy ($1 \leq \alpha \leq 8$) significantly when traffic load is light. It is noted that the network restricts the lightpath length in situation 1. Especially for the COST239 network, the PIC 1 and PIC 2 policies only set up absolutely shortest lightpath in the optical layer in situation 1. This can also avoid long alternate paths and congestion spread. We may conclude that establishing lightpaths in situation 2 is important for maintaining the connectivity of the IP/MPLS layer. The network should establish a lightpath in this case if enough optical resource is available.

To verify our conjecture, we use the ASPR method again (relax the trunk reservation restriction and choose $\alpha = 0$) in the situation 2 to examine the effect of α value on the NSF network performance. So the network uses the TRR method in situation 1 and

ASPR method in situation 2. In this way, the PIC 2 becomes the PIC 3 policy. It is noted that the PIC 3 policy is the same as the PIC 1 policy in the COST239 network if we choose $\beta = 1$. So we only examine the effect of trunk reservation parameter under the PIC 3 policy for the NSF network in Fig. 3.12. It is noted that the PIC 3 policy becomes PIC 1 policy when $\alpha = 0$. The simulation results show that changing the trunk reservation parameter α does not affect the LSP blocking ratio. Based on this observation, we may conclude that NSF network can just choose the absolutely shortest lightpath in situation 1 (the lightpath length restriction in situation 1 becomes $H^{s,d} = D^{s,d}$) and using the ASPR method in situation 2. We name this method as the final PIC policy. The flow chart of the final PIC policy is given in Fig. 3.13.

Fig. 3.12 Blocking ratio vs. TR parameter α under the PIC 3 in the NSF network

Fig. 3.13 The flow chart of PIC policy

In the following, we will use simulation to compare the PIC policy with OHF and OLF policies. We have also obtained 95% confidence intervals for all our results; however, they are so narrow that we omit them from the figures in order to improve readability.

Fig. 3.14 Blocking ratio vs. traffic load for OHF, OLF and PIC policies in the NSF network

Fig. 3.15 Blocking ratio vs. traffic load for OHF, OLF and PIC policies in the COST239 network

In Fig. 3.14 and Fig. 3.15, we have compared the PIC policy with the previously reported OHF and OLF policies for both the NSF and COST239 networks. The simulation conditions remain the same as before. In the PIC policy, β is equal to 1.4 in the NSF network and 1 in the COST239 topology. It is shown that the PIC policy can significantly outperform the other two policies in the COST239 network. In the

NSF network, the OLF policy can outperform the PIC policy marginally when the normalized traffic load is bigger than 3.5 Erlangs. When traffic load is heavy, the IP layer needs more bandwidth to carry incoming traffic flows. However, the NSF network has longer average node pair distance than the more richly connected COST239 network. It has been shown that the lightpath blocking probability increases with the number of lightpath hops [64]. Therefore, a lightpath is more likely to be blocked in the NSF network than in the COST239 network. Since the OLF policy triggers a lightpath establishment for every LSP request, it can potentially set up more lightpaths to give a better performance than the PIC policy. However, when traffic load is light, triggering a lightpath establishment for every LSP will use up idle wavelengths in the optical layer very quickly. As the traffic distribution in the IP layer changes, the optical layer may not have enough idle wavelengths to change the virtual topology. It is shown that the OLF policy cannot decrease the LSP request blocking ratio as fast as the PIC policy does when traffic load decreases. Considering its overall performance, the PIC policy is a better choice as far as LSP request blocking is concerned.

Fig. 3.16 LSP request blocking ratio vs. Add/Drop ratio in the NSF network

Fig. 3.17 LSP request blocking ratio vs. Add/Drop ratio in the COST 239 network

Fibers themselves are often quite abundant in today's infrastructures[57]. Only their equipment with electrical routers or WDM nodes at the endpoints and corresponding network management systems define the value. Reducing the number of transceivers or add/drop ports is one of the most important aims in traffic grooming. In Fig. 3.16 and Fig. 3.17, we show the impact of the add/drop ratio, R , over the network performance under the OHF, OLF and PIC policies. We have shown results here for $\rho = 3.8$ Erlangs in the NSF network and $\rho = 13.6$ Erlangs in the COST239 network. Apart from observing that the PIC policy performs better than the OHF and OLF policies even under these conditions of varying R , we also see the same kind of threshold effects as in [10]. The LSP blocking ratio in the NSF network reaches approximately constant values for $R \geq 6/8$, as observed in [10]. In the COST239 network, the LSP blocking ratio reaches an approximately constant value for $R \geq 7/8$. Beyond the threshold value, further increase in R will increase the cost of the node without any significant performance improvement. The COST239 network needs bigger add/drop ratio value than NSF network to achieve the same network

performance when $R = 1$. This can be explained as follows. A lightpath connects a transmitter and a receiver. Because the NSF network has larger average distance between any pair of nodes than the COST239 network, a pair of transceivers in the NSF network will consume more wavelength resource than in the COST239 network. So the COST239 network will use more transceivers than the NSF network with the same number of wavelengths.

We have also examined these traffic-grooming policies under an unevenly distributed traffic pattern. For this, we use an $N \times N$ matrix to describe the non-uniform traffic model. Here p_{ij} denotes the probability that an LSP request originates from node i and terminates at node j . When a new LSP request arrives, we use this $N \times N$ probability matrix $P = [p_{ij}]$ to determine the source and the destination nodes. The p_{ij} is given by

$$p_{ij} = M_{ij} / S \quad (S = \sum_{i=1}^N \sum_{j=1}^N M_{ij}) \quad (3.9)$$

Fig. 3.18: Blocking ratio vs. traffic load for OHF, OLF and PIC policies in the NSF network under the unevenly distributed model

Fig. 3.19: Blocking ratio vs. traffic load for OHF, OLF and PIC policies in the COST239 network under the unevenly distributed model

Here, we let M_{ij} to be uniformly distributed between 1 and 30 and M_{ij} is set to be 0 for $i = j$. We generate 100 traffic matrixes and plot the average value for all simulation results. Fig. 3.18 and Fig. 3.19 show a comparison between PIC and the OHF and OLF policies using the NSF and COST239 networks. It is noted that we use the add/drop ratio of $R = 6/8$ for NSF network and $R = 7/8$ for COST239 network. The simulation results show that the PIC policy can still significantly outperform OHF and OLF policies in both NSF and COST239 networks.

3.6 Summary

Alternate routing is a practical traffic-engineering tool for evenly distributing traffic in the network according to the link state. Practical algorithms have been implemented in the real telecommunication systems[58, 59]. As the Internet evolves to a multi-service network, the alternate routing will be employed to optimize the overall network

resource utilization. At this time, alternate routing and its congestion spread effect need to be examined again according to the different characteristic of next generation IP/MPLS over reconfigurable WDM networks. In this chapter, we proposed a path inflation index (PII) to evaluate the congestion level caused by alternate routing in the IP/MPLS layer. A new path inflation control (PIC) policy under the overlay model is proposed to limit the spread of congestion in the network. It set up new lightpaths only when the value of PII is likely to exceed a given threshold. Two typical network topologies, e.g. NSF and COST239 networks, have been examined under different traffic grooming policies. Simulation results show that the proposed PIC policy performs significantly better than the more conventional OHF and OLF policies.

Chapter 4 Priority Enabled Dynamic Traffic Grooming

4.1 Introduction

In a system supporting diverse sources, traffic engineering would have the goal of ensuring different traffic performance objectives for different services [60]. The network manager has to guarantee the Quality of Service (QoS) for certain selected service types when traffic load is high. This may be done either by restricting access to bandwidth, or by giving priority access to one type of traffic over another. Such methods are essential to prevent starvation of low-priority flows, to improve the acceptance probability for the high priority flows, and to prevent performance degradation in case of an overload for the network stability.

In the last few years, providing differentiated service in optical network has attracted a lot of attentions [78]. For QoS requirements, we assume peak rate allocation of bandwidth/flow for the duration of an LSP request (Constant Bit Rate: CBR) though the peak rate itself may vary for the different classes. One of the primary performance issues for the various classes would be their respective *LSP Request Blocking Ratios*. In [79], the authors proposed a preemption method to provide differentiated blocking ratio for two classes of traffic in IP over WDM networks. With the preemption method, network resource can be fully utilized. The drawback is that this kind of network can not provide QoS assurance for low priority services. Services for low priority users may be terminated at any time. In this chapter, we study the methods to

provide different *LSP Request Blocking Ratios* for different classes of traffic by blocking or rejecting low priority LSP request in the context of IP over WDM networks.

We have studied the congestion-spread problem in Chapter 3 and proposed the Path Inflation Control (PIC) policy. It is shown that the PIC policy can outperform previous One Hop First (OHF) and Optical Layer First (OLF) policy. In this Chapter, the PIC policy approach is further extended to provide higher/lower LSP request blocking ratios, depending on the traffic class.

4.2 Congestion-based Differentiated Services

The differentiated services (DiffServ) architecture of [61] has been proposed as a scalable approach to providing differentiated services to different classes of traffic in a network. Instead of giving applications and users absolute service level assurances, the network merely assures that higher classes will get better Quality of Service (QoS) than the lower classes. One approach to providing different LSP blocking ratios for different classes of traffic would be to selectively block lower priority traffic. This would keep additional resources available for the higher priority classes so that they encounter less blocking. Since LSP requests arrive randomly, we require some rationale that must be followed to block traffic from the lower priority classes while allowing those from higher priority ones. Moreover, we need to strike a balance between providing better service (less blocking) while keeping path inflation low – as

otherwise, overall service to other (even higher class) traffic flows would also be severely degraded.

The network and traffic models used here are the same as those in Chapter 3. We group the network traffic into M service classes that are ordered such that Class i gets service which is at least as good as or better than Class $(i+1)$ for $M > i \geq 0$ in terms of the LSP request blocking ratio. The class number of the LSP request $r_i^{s,d}$, is the integer value $q_i^{s,d}$ ($M \geq q_i^{s,d} \geq 0$). The *LSP Request Blocking Ratio* for class k traffic in the network is given by

$$P_b^k = 1 - \frac{\sum_s \sum_d \sum_i b_i^{s,d} x_i^{s,d} c_{i,k}^{s,d}}{\sum_s \sum_d \sum_i b_i^{s,d} c_{i,k}^{s,d}} \quad (4.1)$$

where $c_{i,k}^{s,d} = 1$ if $q_i^{s,d} = k$; $c_{i,k}^{s,d} = 0$ otherwise. Here, $x_i^{s,d} = 1$ only if $r_i^{s,d}$ has been routed in the network while $x_i^{s,d} = 0$ if this request was blocked. Note that if we set $c_{i,k}^{s,d} = 1$ for all traffic classes, then (4.1) may be used to compute the overall blocking ratio P_b of the network over all classes of traffic.

To illustrate our approach to tackling multi-class traffic grooming problem, consider a situation where the (single-class) PIC policy of chapter 3 is being used to handle an LSP request from node s to d . We use $r_i^{s,d}$ to denote the i^{th} LSP request from node s to d and let $b_i^{s,d}$ represent the bandwidth required by this LSP request. In this case, a tentative value of the PII, $L_t^{s,d}(\text{new})$, is calculated using (3.8). If using a long LSP will cause the PII value to be greater than the threshold value $\beta D^{s,d}$, then the system may

try to establish a new lightpath between s and d for the request. However, even here, a new lightpath may not always be established and under some conditions the new LSP may still be set up in the existing IP topology even if it leads to increased path inflation and resultant congestion. When the system would not set up a new lightpath between s and d , even though $L_t^{s,d}(\text{new}) > \beta D^{s,d}$, we consider two situations, $\pi 1$ and $\pi 2$.

- Situation $\pi 1$: a lightpath that is connected by idle transceivers and wavelength links from node s to d exists in the optical layer but its length is greater than $D^{s,d}$.
- Situation $\pi 2$: the network does not have enough optical resources, e.g. wavelengths and transceivers, to set up a new lightpath from node s to d .

In situation $\pi 1$, in view of the high path inflation value of this new path, the PIC policy decides to continue to route all classes of traffic in the existing IP topology so that the optical resources are not tied up in an inefficient path. For situation $\pi 2$, the optical resource is used up and the IP layer is also congested in the sense that routing the LSP request through it will also require the use of a feasible path which would lead to $L_t^{s,d}(\text{new}) > \beta D^{s,d}$. We can then opt to provide differentiated services to traffic by blocking lower priority classes in situation $\pi 2$, while still accepting higher priority traffic classes. For a network consisting of only two priority classes (*Class 0*: High Priority and *Class 1*: Low Priority), we give the corresponding algorithm for this in Fig. 4.1 and refer to this as *Algorithm 1*, subsequently.

We study *Algorithm 1* using simulations on the NSF network with 14 nodes and 21

Fig. 4.1 Algorithm 1 for two priority classes of traffic

links and on the COST239 network with 11 nodes and 26 links. For the network topologies, please refer to Fig. 3.6 and Fig. 3.7. Every link in the network has two fibers, transmitting in opposite directions, where each fiber has $W = 8$ wavelengths. The bandwidth of each wavelength is assumed to be unity. For the LSP requests, the bandwidth is assumed to be uniformly distributed in $[0.05, 0.4]$. The end nodes of a new LSP request are randomly generated. We use $R = 6/8$ for the NSF network and $R = 7/8$ for the COST239 network here in correspondence with the priority-less (NP) system studied earlier in chapter 3. We assume that a new LSP request is chosen to be of low priority with probability 0.8 and of high priority with probability 0.2; this gives a 20/80% mix of high/low priorities in the overall traffic. Every simulation run is

repeated ten times with 1,000,000 LSP requests for every run. We have obtained 95% confidence intervals for all our results; however, they are so narrow that we omit them from the figures in order to improve readability.

Fig. 4.2 β effect on the blocking performance under Algorithm 1 for NSF network
with class 0 = 20% and class1 = 80%

Fig. 4.3 β effect on the blocking performance under Algorithm 1 for COST239
network with class 0 = 20% and class1 = 80%

We first examine the effect of β on the network performance. The corresponding simulation results are given in Fig. 4.2 and Fig. 4.3. We use P_b , P_b^0 and P_b^1 are the LSP blocking ratios of the overall traffic, Class-0 traffic and Class-1 traffic respectively. A high and a low traffic load are used for each figure. Note that in all the figures, we use “class $i = x\%$ ” to indicate that class i occupies x percents of the total traffic. Because the COST239 network is denser than the NSF network, we use higher traffic load for COST239 network. This has been explained in chapter 3. The two figures show that Algorithm 1 provides the largest blocking ratio difference when β value is close to 1.0. As the value of β increases, the blocking ratio difference between the two classes of traffic decreases. Since 80% of the traffic load is of low priority, the value of P_b is close to P_b^1 , as would be expected. At high traffic loads, the value of P_b is not affected by the value of β . When traffic load is light, the effect of β on the two networks is different. In the NSF network, the P_b value decreases rapidly first until β exceeds 1.4 and then starts to increase as β increases beyond 1.8, while P_b^0 starts to increase as β exceeds 1.4. In the COST 239 network, the P_b value decreases slowly at first and then increase slowly while the P_b^0 value increase rapidly as β increases beyond 1. Based on these observations, we choose $\beta = 1.4$ for the NSF network and $\beta = 1.0$ for the COST239 network in our subsequent studies of networks under varying traffic loads.

Fig. 4.4 and Fig. 4.5 show the LSP request blocking ratio versus the normalized traffic load per node for *Algorithm 1* for both the NSF and COST239 networks. We use $R = 6/8$ for NSF network and $R = 7/8$ for COST239 network. For comparison, we also show the LSP blocking ratio P_b (PIC-NP) obtained if the original PIC policy with

Fig. 4.4 LSP request blocking performance using Algorithm 1 for NSF network with

$\beta = 1.4$, class 0 = 20% and class1 = 80%

Fig. 4.5 LSP request blocking performance using Algorithm 1 for COST239 network

with $\beta = 1$, class 0 = 20% and class1 = 80%.

no priority (PIC-NP) is used in the network. It is shown that the value of P_b^1 is always more than an order of magnitude higher than that of P_b^0 . Fig. 4.4 and Fig. 4.5 also show that while *Algorithm 1* can provide differentiated services to the two priority classes under high traffic loads (without impairing the overall network performance much) in both topologies, it provides very poor service to the lower priority class and

very poor overall service under light loading. Note that, to some extent, this is caused by the fact that *Algorithm 1* always blocks low priority LSP requests in situation π_2 , even when the overall traffic load is low and system resources are actually available to satisfy the demands of all traffic classes. Note that since resources are under-utilized at low traffic loads, a good algorithm would be one that will provide low blocking in that case to all classes of traffic. This cannot be solved by changing β as we can see from Fig. 4.2 and Fig. 4.3 that the blocking ratio differences for both the high traffic load and the light traffic load decrease at the same rate when β increases. We therefore need some additional network measures that can monitor the traffic load and shut down the differentiated services feature when the traffic load is light.

This problem may be solved by an additional mechanism for monitoring network usage. For this, we introduce an Average Path Inflation Index (APII) parameter which is defined for LSP request $r_k^{s,d}$ as

$$\delta_k^{s,d} = \frac{\sum_{i=1}^{k-1} l_i^{s,d} b_i^{s,d} h_{i,t}^{s,d} x_i^{s,d} + l_k^{s,d} b_k^{s,d} \bar{h}}{\sum_{i=1}^{k-1} b_i^{s,d} h_{i,t}^{s,d} x_i^{s,d} + b_k^{s,d} \bar{h}} \quad (4.3)$$

Here $h_{i,t}^{s,d}$ denotes the holding time of LSP request $r_i^{s,d}$ up to the time instant t at which the LSP request $r_k^{s,d}$ arrives. The average holding time $\bar{h}$ of all LSP requests from s to d , is used as the expected holding time of the new LSP request $r_k^{s,d}$ (since its actual holding time is unknown). $l_i^{s,d}$ denotes that length of the FP calculated for the LSP request $r_i^{s,d}$. We use the APII to evaluate the path usage of previous $k-1$ LSP requests from node s to d . If the traffic load is light, there is enough available bandwidth from node s to d . Most of the LSP requests from node s to d will use ASPs and the APII

value is close to 1. If the traffic load increases, more and more LSP requests from node s to d have to use the AP to exploit the bandwidth resource in the network to avoid blocking. Therefore, the APII value will also increase. We modify *Algorithm 1* so that when a class-1 LSP request faces situation π_2 , the network will choose to route it in the existing IP layer if $APII \leq \beta_1 D^{s,d}$ ($\beta_1 \geq 1$). We refer to this as *Algorithm 2*.

Fig. 4.6 LSP request blocking ratio versus β_1 value using Algorithm 2 for NSF

network with $\beta = 1.4$, class 0 = 20% and class 1 = 80%.

Fig. 4.7 LSP request blocking ratio versus β_1 value using Algorithm 2 for COST239

network with $\beta = 1$, class 0 = 20% and class 1 = 80%.

The effect of using different values of β_1 on the performance of the network is shown in Fig. 4.6 and Fig. 4.7 for both NSF and COST239 networks. Here, we fix β to be 1.4 and 1.0 for the NSF and COST239 networks, respectively. A high and a low traffic load are used for each figure. It can be shown that algorithm 2 would become algorithm 1 if $\beta_1 = 1$. Under the situation $\beta_1 = 1$, a substantial amount of class-1 traffic gets blocked and the QoS difference between the high and low priority classes will be high. As β_1 increases beyond 1, less and less low priority LSP requests are blocked, and the QoS difference between the two classes decreases. It is also observed that as β_1 increases, the three blocking ratios of P_b , P_b^0 and P_b^1 converge faster for the light traffic load case than for the high load case in both figures. These results indicate that we may adjust the degree of QoS differentiation between traffic classes by tuning the value of β_1 . Note that while we want to provide differentiated services for the two traffic classes when traffic load is heavy, we also want the network to show good overall performance for all traffic loads, even at low traffic. For Algorithm 2, $\beta_1=1.2$

Fig. 4.8 LSP Request blocking ratio versus traffic load per node using Algorithm 2 for

NSF network with $\beta = 1.4$, $\beta_1 = 1.2$, class 0 = 20% and class 1 = 80%

Fig. 4.9 LSP request blocking ratio versus traffic load per node using Algorithm2 for

COST239 Network with $\beta = 1.0$, $\beta_l = 1.4$, class 0 = 20% and class1 = 80%

and $\beta_l=1.4$ seems to be a good overall choices for operating the NSF and COST239 networks respectively. We use these subsequently for the study of networks under varying traffic load.

Fig. 4.8 and Fig. 4.9 show the LSP request blocking ratio versus the normalized traffic load per node for Algorithm 2 in both the NSF and COST239 networks. For comparison, we also show the LSP blocking ratio P_b (PIC-NP) obtained if the original PIC policy with no priority (PIC-NP) is used in the network. When $\rho = 6.5$ Erlangs in the NSF network and $\rho = 16.5$ Erlangs in the COST239 network, the value of P_b^0 is about 1 order of magnitude smaller than the value of P_b^l . When $\rho = 3.5$ Erlangs in the NSF network and $\rho = 13$ Erlangs in the COST239 network, the value of P_b^0 is almost the same as the value of P_b^l . Both figures show the desirable feature that, unlike *Algorithm 1*, *Algorithm 2* not only provides differentiated services when traffic load is high but also gives significantly low blocking for the lower priority class LSP requests

and for the overall traffic at low traffic loads. The differentiated service can be disabled when traffic load is light. Note that this happens primarily because, unlike *Algorithm 1*, *Algorithm 2* does not summarily block lower priority LSP requests at low traffic loads when the overall system is lightly loaded anyway and resources are available for all LSP requests.

Fig. 4.10 LSP request blocking ratio versus traffic load per node using Algorithm 2

for NSF network with $\beta = 1.4$, $\beta_l = 1.2$, class 0 = 50% and class1=50%

Fig. 4.11 LSP Request blocking ratio versus traffic load per node using Algorithm 2

for COST239 Network with $\beta = 1.0$, $\beta_l = 1.4$, class 0 = 50% and class1 = 50%

In Fig. 4.10 and Fig. 4.11, we change the traffic type mix so that both the traffic classes contribute equal amounts of traffic for both NSF network and COST239 network. The other parameters are the same as in Fig. 4.8 and Fig. 4.9, respectively. To our surprise, we observe similar results. The results show the same trends, as in Fig. 4.8 and Fig. 4.9 respectively, though the results of Fig. 4.10 and Fig. 4.11 are marginally poorer. (This is to be expected given the higher percentage of low priority traffic in the latter case.) This indicates that the proposed Algorithm 2 provides robust performance improvement, even with different mixes of the traffic from the two priority classes.

Fig. 4.12 The flow char of Algorithm 2 with three classes of traffic

It may be noted that our approach can also handle more than two priority classes by decreasing the threshold value of APII as the number of classes increases. This will affect the probability of the new LSP request being accepted in situation π_2 and will result in different blocking ratios for different traffic classes. As an example, we consider expanding Algorithm 2 from two to three priority classes of traffic. We use two threshold values β_1 and β_2 ($\beta_1 > \beta_2$) to determine the acceptance of class-1 and class-2 traffic, respectively. The class-0 traffic has the highest priority. The corresponding flow chart is given in Fig. 4.12.

We have done simulation studies with the three-class traffic model in which we assume that a new LSP request is chosen to be of priority 0 with probability 0.1, of priority 1 with probability 0.2, and of priority 1 with probability 0.7; this gives a 10/20/70% mix of Class 0/ Class 1/ Class 2 traffic in the overall traffic. We choose $\beta_1 = 1.5$ and $\beta_2 = 1.2$ for the NSF network and choose $\beta_1 = 1.5$ and $\beta_2 = 1.4$ for the COST239 network. Fig. 4.13 and Fig. 4.14 show the simulation results. When $\rho = 6.5$ Erlangs in the NSF network and $\rho = 16.5$ Erlangs in the COST239 network, the value of P_b^0 is about 1 order of magnitude smaller than the value of P_b^2 . The value of P_b^1 is at the middle between the value of P_b^0 and the value of P_b^2 . When $\rho = 3.5$ Erlangs in the NSF network and $\rho = 13$ Erlangs in the COST239 network, the value of P_b^0 , P_b^1 , P_b^2 are almost the same. The network can not only provide differentiated services for three classes traffic when the traffic load is high but also gives good performance for the overall traffic when the traffic load is light.

Fig. 4.13 LSP request blocking ratio versus traffic load per node using Algorithm 2 for NSF network with $\beta = 1.4$, $\beta_1 = 1.5$, $\beta_2 = 1.2$, class 0 = 10%, class 1 = 20% and class 2 = 70%

Fig. 4.14 LSP Request blocking ratio versus traffic load per node using Algorithm 2 for COST239 network with $\beta = 1.0$, $\beta_1 = 1.5$, $\beta_2 = 1.4$, class 0 = 10% class 1 = 20%, and class 2 = 70%

Note that the APII computation using (4.3) actually uses all the past LSP routing data to evaluate this parameter. However, this is not a good computational strategy, as it

tends to take into account the routing information regardless of its age. For this, a more adaptive strategy will be to ignore older routing data while using the more current ones. We do this by using an integer window parameter ω in (4.3), which forces the APII computation to ignore the effect of older LSPs. (Other similar approaches, such as using lower weights for older routing information along with the windowing approach, are also possible and perform similarly.)

$$\delta_{k,\omega}^{s,d} = \frac{\sum_{i=k-\omega}^{k-1} l_i^{s,d} b_i^{s,d} h_{i,t}^{s,d} x_i^{s,d} + l_k^{s,d} b_k^{s,d} \bar{h}}{\sum_{i=k-\omega}^{k-1} b_i^{s,d} h_{i,t}^{s,d} x_i^{s,d} + b_k^{s,d} \bar{h}}, \quad (\omega \geq 1) \quad (4.3)$$

Using this modified APII gives us *Algorithm 3*. Note that, *Algorithms 3* and *2* are the same for $\omega = k-1$. For ω smaller than $k-1$, the routing information and bandwidth value of LSPs with index smaller than $k-\omega$ (i.e. earlier LSPs) will not affect the APII calculations as given by (4.3). It is evident that the network will adapt to traffic load fluctuations faster if smaller values of ω are used. However, the trade-off in this case is that for smaller ω it would be more difficult to accurately evaluate network usage.

Here, we still use the two-class traffic model with a 20/80% mix of high/low priorities. In our simulation studies, we chose $\omega = 16$ (i.e. the routing information of only the latest 15 LSPs are used) for both network topologies and choose $\beta_1 = 1.6$ and $\beta_1 = 1.2$, respectively, for NSF network and COST239 network as illustrative values.

Fig. 4.15 and Fig. 4.16 compare the performance of *Algorithms 1* and *3* when a dynamically fluctuating traffic load is offered to both NSF and COST239 network

Fig. 4.15 Comparative blocking Performance for Algorithm 1 (A1) and Algorithm 3 (A3) for NSF network with $\beta = 1.4$, $\beta_I = 1.6$ and $\omega = 16$

Fig. 4.16 Comparative blocking performance for Algorithm 1 (A1) and Algorithm 3 (A3) for COST239 network with $\beta = 1.0$, $\beta_I = 1.2$ and $\omega = 16$

respectively. In this case, the dynamic conditions are simulated by keeping the average holding time of LSP requests fixed but changing the arrival rate after every

40,000 LSP request arrivals; for each time interval, the corresponding offered traffic load is shown on the upper x-axis of both Fig. 4.15 and Fig. 4.16. Note that while both *Algorithms* 1 and 3 show that they can adapt to traffic fluctuations, the performance of *Algorithm* 3 is much better overall. When the number of requests is between 50000 to 80000, the difference between the value of P_b^0 and P_b^1 is about 1.5 orders of magnitude under the algorithm 1 and about 0.5 orders of magnitude under the algorithm 3. *Algorithm* 3 blocks class-1 traffic much less than *Algorithm* 1 at low traffic loads (i.e. 3.5 Erlangs for NSF network and 13 Erlangs for COST239 network). However, this happens at the cost of an increase in the blocking for the class 0 traffic when traffic load is heavy. It is also noted that the network performance may be “tuned” by choosing the value of β_1 and ω to suit the performance objective one has in mind. These parameters may depend on the pricing and traffic models used in a real network and the source models used for the different classes of traffic. This would also control the extent of service differentiation that may be obtained between the various classes. For example, a small β_1 value will be chosen if the high priority users contribute most of the revenue.

4.3 Summary

In this study, we discussed methods to provide differentiated LSP request blocking ratios for different priority traffic in the dynamic traffic grooming networks. Based on the understanding of the congestion-spread problem in chapter 3, we extend the path inflation control (PIC) strategy to handle networks and service scenarios with traffic of different priority classes where differentiated services have to be provided. We have proposed 3 algorithms for doing this and have studied their performance by

simulation networks, e.g. NSF and COST239 networks. In this study, the main idea is to block a low priority LSP request if accepting it will cause the value of PII to exceed a given threshold but there is not enough optical resource for setting up a lightpath for the congested link. This method is named as Algorithm 1. The simulation results show that the network with Algorithm 1 can provide differentiated service. It is noted that the network has enough bandwidth and all traffic demands can be accepted when traffic load is light. However, the network under Algorithm 1 cannot adapt itself to the light traffic case and result high blocking ratio for overall traffic. We propose the APII index to monitor the traffic load in the network and decide whether or not to accept a low priority LSP request when the value of PII will increase beyond a threshold value. With this, Algorithm 1 becomes Algorithm 2. The simulation results show that the network with Algorithm 2 not only provides differentiated services when traffic load is high but also gives significantly low blocking for the lower priority class LSP requests and for the overall traffic at low traffic loads. The algorithm 2 has also been extended to provide differentiated service for more than two classes of traffic. To cope with the fluctuation traffic in the network, the APII is modified and only recent several LSPs are used to calculate the value of APII. The algorithm 3 with the new APII index was found to work well under dynamically fluctuating traffic loads.

Chapter 5 Applying Saturated Cut Method for Dynamic Traffic Grooming in IP/MPLS over WDM Networks

5.1 Introduction

Even though the overlay model is simpler and more feasible to implement with current technology than the peer model as discussed in Chapter 2, it was shown that the overlay model has lower efficiency than the peer model[38]. This is because, in the peer model, the spare capacity in the IP/MPLS layer and the free wavelengths in the optical layer are considered jointly to find a shortest route. However, in the overlay model, routing instances in the IP/MPLS layer are independent of that in the optical layer. The IP/MPLS layer in the overlay model has to figure out how to trigger a lightpath establishment without knowing the optical layer topology information. All of the existing traffic grooming policies under the overlay model, e.g. the *IP Layer First* (ILF) [10] , OLF, OHF and PIC policies, only request one lightpath establishment from source node to the destination node of an LSP request.

Consider an example in Fig. 5.1 which shows a three node IP/MPLS over WDM network. In the optical layer, each link has two wavelengths transmitting in opposite directions. The dashed arrows denote the occupied wavelengths that provide bandwidth for the IP/MPLS layer. The solid arrow denotes the presence of idle

Fig. 5.1 An example of traffic grooming in IP/MPLS over WDM networks

wavelength on the link. In Fig. 5.1, there is only one idle wavelength from OXC B to C in the optical layer. When an LSP request r^{ac} arrives from LSR a to c and demands bandwidth b , only link a - b in the IP/MPLS layer has enough available bandwidth for r^{ac} . This implies that a new lightpath needs to be set up from LSR a to c in all the policies, i.e. the OHF, OLF and ILF policies and the PIC policy proposed by us earlier. As there are not enough wavelengths in the optical layer for setting up a lightpath from LSR a to c , the LSP request r^{ac} will get blocked under all of these policies (ILF, OHF, OLF and PIC). In order to effectively combine the two-layer topology information for greater efficiency, we can choose to set up a lightpath from node b to c so that a two-hop LSP a - b - c from node a to c can then be established in the IP/MPLS layer. This would not be feasible to do under the ILF, OHF, OLF and PIC policies as the IP/MPLS layer in the overlay model cannot see the topology details of the optical layer but can only ask for a lightpath to be established between the source-

destination nodes. If we can exploit the topology information in the IP/MPLS and generate appropriate lightpath requests, we may further decrease the LSP request blocking ratio in situations like that of Fig. 5.1. In this work, we consider extracting some useful topology information in the IP/MPLS layer for the smart triggering lightpath establishment to further decrease the LSP blocking ratio in the IP/MPLS over WDM networks under the overlay model.

For this, we introduce the saturated cut (SC) [22] method into the traffic grooming policies proposed by us earlier. This further improves the chances of lightpath establishment (thereby reducing LSP request blocking ratio) while still allowing the network resources to be efficiently used. The rest of this chapter is organized as follows. The key ideas of the saturated cut (SC) method are introduced in Section 2. The application details of the SC methods in the PIC policy are given in Section 3. In Section 4, the PIC policies with/without SC methods are studied and compared using simulation networks. The time complexity of the PIC policy and the PIC policy with the SC methods are given in Section 5. The heuristic partial saturated cut (PSC) methods are proposed and the simulation results are shown in section 6. In section 7, the conclusion is given.

5.2 The Saturated Cut Method

The saturated cut (SC) method is an efficient method for designing electronic information networks [22]. It seeks to identify a partition (or cut) of the nodes of the network into two sets X and $\bar{X}$ such that the links joining X and $\bar{X}$ are highly utilized. If a SC exists between X and $\bar{X}$, then it seems plausible that adding a link between a

node in X and a node in $\underline{X}$ will help reduce the high level of utilization across the cut. It may be noted that this is a general methodology for network topology design. For a specific problem, the details of the method would need to be appropriately formulated such that the problem's specific features are best exploited[62].

Fig. 5.2 Saturated cut in the IP/MPLS over WDM network

If we consider the utilization level of a link in the IP/MPLS layer as the occupied bandwidth of the link, setting up a lightpath for the SC may reduce the overall blocking ratio. This is because available bandwidth across a SC is less than the available bandwidth across the other cuts in the network and the connection requests which travel across the SC will be more likely to be blocked. If we consider the path length in the IP/MPLS layer as the utilization level, setting up a shortest lightpath for the SC may reduce the average node distance of the IP/MPLS network and increase the routing efficiency. In the following, we introduce methods to find two kinds of SCs in the IP/MPLS layer and choose to set up a shortest lightpath for the SCs under the PIC policy.

5.3 Applying SC method

In this chapter, we use the same routing method in the IP/MPLS and optical layers as in the chapter 3. The feasible topology V in the IP/MPLS layer consists of LSRs and the feasible lightpaths whose available bandwidth is greater than or equal to the bandwidth of the newly arrived LSP request. A shortest path found in V for the LSP request is called the feasible path (FP). The dynamic topology A of the optical layer consists of the idle wavelengths and the OXCs. The methods to find the feasible topology V and dynamic topology of A are given in Chapter 3.

The PIC policy defines a Path Inflation Index (PII) between two nodes to evaluate the congestion degree (i.e. the inflation augmentation) in the IP/MPLS network [63]. When a new LSP request $r_k^{s,d}$ arrives at time t and a FP in the IP/MPLS network with length $l_k^{s,d}$ is found for it, the tentative PII is calculated using (3.8) as in chapter 3. If $l_k^{s,d} < \beta D^{s,d}$ or $(l_k^{s,d} > \beta D^{s,d} \text{ and } L_t^{s,d}(\text{new}) \leq \beta D^{s,d})$ ($\beta \geq 1$), the LSP request is routed using the FP. If $l_k^{s,d} > \beta D^{s,d}$ and $L_t^{s,d}(\text{new}) > \beta D^{s,d}$ ($\beta \geq 1$), the PIC policy prefers to avoid the current FP path for $r_k^{s,d}$ so as to limit the spread of congestion caused by long path routing. Here, $D^{s,d}$ is the hop distance between node s and d in the physical topology. Instead, it tries to set up a new lightpath directly from s to d with length $H^{s,d} \leq D^{s,d}$ to reduce the congestion in the network; otherwise, it routes the LSP request in the IP/MPLS layer. As a result, an LSP request will not be blocked in PIC policy if a FP is found. If a FP cannot be found, a connection request will be transferred to the optical layer for setting up a lightpath from node s to d . If a lightpath can not be set up, the LSP request will be blocked. The acceptance of such lightpath will decide the

acceptance of the LSP request. The PIC policy to route the LSP request and decide whether or not to set up a new lightpath from s to d is then given in Fig. 5.3.

Fig. 5.3 The illustration of situation A and situation B in the flow chart for the PIC Policy

We define two kinds of SCs under the PIC policy. For the first kind of the SC, we use availability of feasible lightpaths between nodes to evaluate the usage degree of links. The first kind of the SC is detected between node s and d when a FP for LSP request $r_i^{s,d}$ cannot be found in the IP/MPLS layer. We call this situation A (SA) as shown in

Fig. 5.3. The distance from node i to j in feasible topology V is denoted by $l(i, j)$. If $i = j$, $l(i, j) = 0$; if there is no FP from node i to j , $l(i, j) = \infty$. Therefore, the *source island* is denoted by $X_1 = \{j \mid l(s, j) < \infty\}$. It is a node set consisting of node s and the nodes in V that can be reached from s . The *destination island* is denoted by $\underline{X}_1 = \{i \mid l(i, d) < \infty\}$. This is the node set consisting of node d and the nodes in V that can reach node d . These source and destination islands may be found using the breadth-first algorithm or Dijkstra algorithm[54]. Clearly, $X_1 \cap \underline{X}_1 = \emptyset$. We call the cut $(X_1, \underline{X}_1)$ as the first kind of SC for the LSP request $r_i^{s,d}$ in the virtual topology. If a new lightpath is now set up from X_1 to $\underline{X}_1$, then we will once again have a FP from s to d in the IP/MPLS layer. The optical layer calculates this by finding the shortest paths from each node in X_1 to each node in $\underline{X}_1$ and choosing the shortest one and the tie is randomly broken. We subsequently refer to this method as the *Full SC Method 1* (FSC1).

For the second kind of the SC, we use the distance of a node pair in V to evaluate the path usage degree between node pairs. We denote by $l(i, j)$ the distance from node i to j in the feasible topology V . If a FP can be found, $(L_i^{s,d}(\text{new}) > \beta D^{s,d})$ and $(l_k^{s,d} > \beta D^{s,d})$, we refer to this as situation B as shown in Fig. 5.3. In situation B , we use the following method to find the source and destination islands for the second kind of the SC. The distance from node s to other nodes and the distance from other nodes to the node d in V can be calculated by using the Dijkstra algorithm [54] twice. If $l(s, i) \leq \beta D(s, i)$, we include node i in the source island X_2 . If $l(j, d) \leq \beta D(j, d)$, we include node j in the destination island $\underline{X}_2$. After the set X_2 and $\underline{X}_2$ have been generated, there

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may be some nodes belonging to the intersection of X_2 and $\underline{X}_2$. To satisfy the condition $X_2 \cap \underline{X}_2 = \emptyset$. We deal with the node $k \in X_1 \cap \underline{X}_2$ as follows

```

if  $l(s, k) < l(k, d)$ , delete node  $k$  in  $\underline{X}_2$ .
else
  If  $l(s, k) > l(k, d)$ , delete node  $k$  in  $X_2$ .
  else
    If  $l(s, k) = l(k, d)$ , delete node  $k$  in either  $X_2$  or  $\underline{X}_2$  randomly.

```

After the islands are determined, this island information is transferred to the optical layer through the user network interface (UNI). If H_{ij} denotes the length of a lightpath that connects X_2 and $\underline{X}_2$, we use following method to decide whether or not to set up the lightpath. The new distance from s to d in the IP/MPSL layer is denoted by $(l(s, i) + H_{ij} + l(j, d))$. If $\min_{i,j} (l(s, i) + H_{ij} + l(j, d)) \leq \beta D^{s,d}$, the shortest lightpath from node i to j will be set up and the LSP request will be routed in the new virtual topology; otherwise, the LSP request gets routed in the existing virtual topology as before. In order to get the best possible performance that can be obtained in this fashion, we propose the *Full SC Method 2* (FSC2) in which we not only set up a lightpath for the first kind of SC but also for the second kind of SC.

5.4 Time Complexity of the PIC policy with the Saturated cut method.

In the original PIC policy, the network first uses a Dijkstra algorithm to calculate a FP for an LSP request. Subsequently, the network chooses whether to set up a new lightpath or not for accepting the LSP request. Three different situations may be encountered in the process of routing a new LSP request. In situation 1, the FP can not be found and a lightpath needs to be set up from node s to d in the optical layer. The LSP request is then routed in the new lighpath. The PIC policy needs to execute the

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Dijkstra algorithm twice for routing the LSP request. In situation 2, the FP can be found but $L_t^{s,d} > \beta D^{s,d}$ because $l_i^{s,d} > \beta D^{s,d}$. The PIC policy needs to calculate the value of PII and calculate a lightpath from node s to d after finding the FP. In situation 3, if FP can be found and $L_t^{s,d} \leq \beta D^{s,d}$, or $l_i^{s,d} < \beta D^{s,d}$, the LSP request is routed in the existing IP/MPLS layer. Therefore, situation 2 would be the computationally worst case scenario where the PIC policy has to calculate the value of PII and use the Dijkstra algorithms twice to calculate the FP and the lightpaths. In a capacitated network, we denoted by $M^{s,d}$ the maximum flow that can be send from node s to node d . The node degree of node i is denoted by ψ_i . So $M^{s,d} \leq \min\{\psi_s, \psi_d\}$. So the maximum flow in the network is $M \leq \max_i\{\psi_i\}$. If the maximum flow in the network is M and the minimum bandwidth of an LSP request is B_{min} , then a maximum of $\zeta = \lfloor M/B_{min} \rfloor \leq \lfloor \min_i(\psi_i)/B_{min} \rfloor$ LSP requests need to be counted for calculating the PII between a node pair in the network. This implies that calculating a PII would be done in $O(\zeta)$ time. Since the time complexity of Dijkstra algorithm is $O(N^2)$ [54], the running time of original PIC policy is in $O(N^2 + \zeta) \leq O(N^2 + \lfloor \min_i(\psi_i)/B_{min} \rfloor)$. Generally, the value of $\min_i(\psi_i)$ will not increase at the same rate as the value of N , so the running time of original PIC policy is in $O(N^2 + \lfloor \min_i(\psi_i)/B_{min} \rfloor) = O(N^2)$ time.

Compared with the original PIC policy (which only requests a lightpath from source node s to the destination node d of an LSP request), the saturated cut method can

choose to set up the shortest lightpath from the source island to the destination island. The optical layer calculates this by finding the shortest paths from each node in X to each node in $\underline{X}$ and choosing the shortest one to connect X and $\underline{X}$. We use the breadth-first[54] and Dijkstra algorithms[54] twice, respectively, to find the islands of the first kind and of the second kind for the saturated cut method. The running time of the breadth-first algorithm is $O(N+E)$ [54]. In the worst case, $(N/2)^2$ lightpaths need to be calculated between two islands and their lengths are compared for finding the shortest one. Thus, the time complexity of the FSC1 and FSC2 method is dominated by $(N/2)^2$ times the running time of a Dijkstra algorithm. Therefore, a lightpath can be calculated in $O(N^4)$ time for both the FSC1 method and the FSC2 method. The running time of the PIC policy with FSC1 or FSC2 method is also in $O(N^4)$ time, which may be too high to be suitable for online traffic grooming. With this problem in mind, we propose a heuristic modification for the SC method in order to reduce the running time. This is given next.

5.5 Partial Saturated Cut Method

In order to substantially reduce the running time of the SC method, we present a heuristic algorithm to set up a lightpath between X and $\underline{X}$. Since this heuristic algorithm calculates lightpaths for only a few node pairs (rather than all the node pairs as done for the full SC), we refer to it as a *Partial SC Method* (PSC). It may be noted that for a given network, its physical topology would be fixed, and hence the shortest distance between any two nodes can be pre-calculated.

For the first kind of saturated cut, the network orders the node pairs in a queue according to the distance between them. For the second kind of saturated cut, the network orders the node pairs in the queue according to the value of $(l(s, i) + D^{ij} + l(j, d))$ ($i \in X_2, j \in \underline{X}_2$). Instead of calculating all paths between every node pair in the optical layer, we choose to calculate only limited lightpaths for the S node pairs at the head of the queue. (If there is only one node pair (s, d) , we only calculate one lightpath from node s to d). With this modification, the FSC1 and FSC2 methods become the PSC1 and PSC2 methods, respectively. If the PIC 1 and PIC 2 methods with small S value can achieve almost the same performance of the FSC1 and FSC 2 methods, the algorithm complexity can be decreased from $O(N^4)$ to $O(N^2)$. We will study this using simulation in the next section.

5.6 Simulation Results

We have used simulations to study the performance of our proposed PIC policy where the SC approach proposed in the earlier section has been applied. These have been carried out for the typical NSF topology with 14 nodes and 21 links and the COST239 topology with 11 nodes and 26 links as shown in Fig. 3.8 and Fig. 3.9, respectively. The average node degree in the NSF topology and COST239 topology are 3 and 4.72 respectively. The average fibre-hop distances between nodes in the two topologies are 2.14 and 1.56 respectively. Consequently, we can see that the COST239 topology has a higher average node degree and a shorter average node distance than the NSF topology, i.e. the NSF topology is “sparser” than the COST239 topology or, alternatively, that the COST239 topology is “denser” than NSF topology. In this chapter, we use the same network and traffic model given in Chapter 3. For both

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topologies, we assume each link to have $W = 8$ wavelengths in each direction where the capacity of each wavelength is taken to be unity. The bandwidths of the LSP requests are assumed to be uniformly distributed in $[0.05, 0.4]$. The number of transceivers is equal to the number of add/drop ports at each node. Since this determines the main cost of the node, it would be important to keep the total number of transmitters and receivers low in order to do traffic grooming economically in IP/MPLS over WDM networks. As a measure of this, we use the *Add/Drop Ratio* R which has been defined earlier in (3.3). For the results reported here, every simulation run has been repeated 10 times with 1,000,000 LSP requests for every run, and results have been averaged. We have also obtained 95% confidence intervals for our results and have indicated them in the figures given.

We first examine the effect of β on the network performance under a uniformly distributed traffic model. The normalized traffic load per node and LSP request blocking ratio are denoted by ρ and P_b . (These parameters have been defined earlier in Chapter 3.) To show illustrative results, we choose three different values of ρ such that the LSP request blocking ratio under the PIC policy with FSC1 method are approximately 10^{-2} , 10^{-3} and 10^{-4} for these values.

Fig. 5.4 and Fig. 5.5 show the simulation results of the NSF network and COST239 network respectively. In each figure, we examine both the PIC policy with the FSC1 method and the PIC policy with the FSC2 method. Here, we use P_b to represent the LSP request blocking ratio. For the NSF network, Fig. 5.4 shows that the network-blocking ratio starts to increase as the β value increases beyond 1.4 and 1.0

Fig. 5.4 LSP request blocking ratio vs. the value of β under the PIC policy, the PIC with the FSC1 method and the PIC with the FSC2 method in the NSF topology

Fig. 5.5 LSP request blocking ratio vs. the value of β under the PIC policy, the PIC with the FSC1 method and the PIC with the FSC2 method in the COST239 topology

respectively for FSC1 and FSC2 methods. For the COST239 network, Fig. 5.5 shows the network blocking ratio starts to increase as soon as the value of β increases beyond 1 for both FSC1 and FSC2 method. It is noted that the PIC policy will become the ILF policy when $\beta = \infty$. The FSC2 method clearly outperforms the FSC 1 method in all cases and choosing $\beta = 1$ appears to be a good choice for the both networks under

both the FSC1 and FSC2 methods. When $\beta = 1$, the PIC policy will trigger a lightpath establishment whenever an ASP cannot be found in IP/MPLS layer. In this situation, the network manager does not need to calculate PII. We call it as the Absolutely Shortest Path First (ASPF) policy. The flow chart of the ASPF policy with the FSC 2 method is given in Fig. 5.6. We also give results on using this ASPF policy with both the FSC1 and FSC2 methods in the NSF and COST239 networks.

Fig. 5.6 Flow chart of absolutely shortest path first (ASPF) policy with the FSC 2 method

Fig. 5.7 Blocking performance with different traffic grooming policies in the NSF topology

Fig. 5.8 Blocking performance with different traffic grooming policies in the COST239 topology

In Fig. 5.7 and Fig. 5.8, we have compared the three traffic grooming policies, i.e., the PIC policy, the ASPF policy with the FSC1 method and the ASPF policy with the FSC2 method, for the NSF and COST 239 networks, respectively. As shown in chapter 3, the NSF network and the COST239 network achieve good blocking

performance with $\beta = 1.4$ and $\beta = 1.0$ respectively. We, therefore, continue to use these values for the NSF network and the COSR239 network simulations reported here. It may be noted that when $\beta = 1.0$, the PIC policy becomes the ASPF policy. As expected, the FSC1 and FSC2 methods lead to less blocking than the original PIC policy in both networks. This is because the FSC1 method can enhance the lightpath establishment capability by calculating lightpaths between two islands rather than two nodes in situation A. Besides enhancing the lightpath establishment capability in situation 1, the FSC2 method can provide more choices for setting up shorter lightpaths in situation B so as to prevent the spread of congestion in the IP/MPLS layer. This further reduces the LSP request blocking ratio.

It was also noticed that both the FSC1 and FSC2 methods are more effective at improving the blocking performance of the NSF network than that of the COST239 network. This is because the NSF topology is sparser than the COST239 topology. When a new connection request arrives in the optical layer, there will be fewer paths in the NSF network than in the COST239 network under the PIC policy. The SC method will increase the lightpath establishing choices more in the NSF network than in the COST239 network.

The number of transceivers is equal to the number of add/drop ports at each node. Since this determines the main cost of the node, it would be important to keep the total number of transmitters and receivers low in order to do traffic grooming economically in IP/MPLS over WDM networks. In Fig. 5.9 and Fig. 5.10, we show the impact of the add/drop ratio on performance for the NSF and COST239 networks

Fig. 5.9 Blocking performance with varying Add/Drop Ratios in NSF network

Fig. 5.10 Blocking performance with varying Add/Drop Ratios in COST239 network

under different traffic grooming policies. We observe that for low values of R , performance is virtually the same for systems under different traffic grooming policies. As the R value increases further, we can still decrease P_b , but a threshold for this is reached for $R \geq 6/8$ and $R \geq 7/8$ respectively in the NSF network and the COST239 network. This implies that there is little or no advantage in incurring higher

implementation costs beyond this threshold value of R . The COST239 network needs bigger add/drop ratio value than the NSF network to achieve the same network performance when $R = 1$. This can be explained as follows. Because the COST239 network has smaller average node pair distance than the NSF network, the IP/MPLS layer in the COST239 network will request more one-fibre-hop connections than in NSF network. The optical layer in the COST239 network will set up more one-fibre-hop lightpaths and use more transceivers than the NSF network. In the rest of the paper, we will use $R = 6/8$ for the NSF network and $R=7/8$ for the COST239 network.

Although FSC1 and FSC2 methods can improve the network performance significantly for the NSF network, its high complexity of $O(N^4)$ prevents it from being applying in real system. In Fig. 11, we have examined the effect of S value in the ASPF method with PSC1 and PSC2 methods in the NSF network. The add/drop ratio is equal to 6/8.

Fig. 5.11 The effect of the number of node pairs under the ASPF policy with the PSC1 method and the PSC2 method

Here, we choose two traffic loads such that the lowest LSP request blocking ratio is around 10^{-3} and 10^{-4} . It is noted that the network performance can be improved by PSC1 and PSC2 method even if we just use $S=1$ (i.e. with one node pair) compared to the original PIC policy. This is because, with the SC method, the optical layer can choose a shorter lightpath (between the islands) than the lightpath between the end nodes of the LSP request. This will save on the wavelengths and will improve the success rate for setting up lightpaths because short lightpaths will encounter less blocking than long lightpaths [64, 65]. The LSP request-blocking ratio reaches approximately constant values for $S \geq 3$ for both PSC1 and PSC 2 methods. (It may be noted that there are a maximum of 49 lightpaths that cross the saturated cut.) Increasing S beyond this value increases the algorithm complexity without significantly improving its performance. If we choose $S = 3$, the PSC method needs to run the Dijkstra algorithms only three times to calculate lightpaths, and then chooses the shorter one to connect X and $\underline{X}$. Hence, the running time of the PSC1 and PSC2 method would only be $O(N^2)$, not $O(N^4)$.

5.7 Summary

To decrease the blocking ratio and maximize the revenue are the most important tasks for the network manager. In this chapter, we have applied the saturated cut (SC) method to the PIC traffic grooming policy for further decreasing the LSP request-blocking ratio. The SC method can exploit the IP/MPLS layer topology information and provide more than one choice for setting up a lightpath in the optical layer. On comparison, the previously proposed traffic grooming policy just set up a lightpath directly between the end nodes of a new LSP request. This may decrease the lightpath

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blocking ratio, and further improve the overall network performance. Two kinds of SCs have been defined in this chapter. The first kind of SC happens when there is not enough bandwidth to connect the end nodes of a new LSP request. The second kind of SC happens when the path for the new LSP request is too long. We have used simulations to study the efficiency of the SC methods under different conditions and for two different networks. For the sparse NSF network, the simulation results show that the SC method can improve the LSP request blocking ratio by an order of magnitude or more. For the dense COST239 network, the optical layer already has a lot of alternate path choices available to it. Therefore, applying the SC method in the COST239 network does not improve network performance as much as in the case of the NSF network. Finally, heuristic modifications (partial SC methods) have been presented which provide almost the same level of performance as the full SC methods but with much lower computational complexity.

Chapter 6 Dynamic Multicast Traffic Grooming in IP/MPLS over WDM Networks

6.1 Introduction

The increasing popularity of multicast services such as Internet Protocol television (IPTV), video conferencing, distance learning and multi-player on-line gaming is expected to be a major contributor to the growth in Internet traffic demand. These services and applications are quite demanding in the bandwidth and service quality that they require (i.e. the assurance of bandwidth availability during the life of a particular service scenario). They are also inherently applications that require the simultaneous transmission of information from one source to multiple destinations. Multicasting will be efficient in these applications as it would eliminate the need for the source to send an individual copy of the information to each destination. As optical switching technology advances, the optical network will not only provide lightpath connections but can also set up *light trees* [66] by splitting light power appropriately. Since IP/MPLS multicast functions have already been implemented in routers, two different multicast traffic-grooming methods are feasible. One is to groom the IP/MPLS multicast requests into the unicast WDM network. The other is to groom the IP/MPLS multicast requests into the multicast WDM network. Optical multicasting [67], [68] avoids burdening nodes with the task of copying data electrically. Aggregating sub-wavelength multicast requests into light trees has attracted increasing research interests [69, 70]. However, finding a good aggregated tree for a variety of multicast services is still difficult as different multicast services

will generally not have the same user group [71]. In that case, if the aggregated tree covers all the terminal nodes of all these multicast requests, then some of the tree leaves would not be terminal nodes of some of the multicast requests. This implies that the data packet from the source will “leak” to these unrelated tree leaves, leading to wastage of bandwidth. On the other hand, if an aggregated tree only covers the intersection of several multicast requests, then some multicast requests will be forced to use other unicast paths in the lower layer to complete the required service. In addition, we also need to account for the requirement that a big light tree will require a large number of multicast requests to be aggregated into itself for efficient usage.

The work reported in this chapter deals with dynamic multicast traffic grooming in IP/MPLS over mesh, unicast, WDM networks. We use bandwidth guaranteed label switched paths (LSP) in the IP/MPLS layer. The application scenarios considered are ones where multicast connection requests with different bandwidth requirements arrive and leave randomly. Based on the relationship between the control planes of the IP/MPLS and optical layers, the architecture of IP/MPLS over optical networks can be classified into either the *overlay* or the *peer* model [40]. We consider the overlay model here for it is simpler and more feasible for current implementation, as explained in Chapter 3. In Section 6.2, we present the network and traffic models that are considered. Section 6.3 describes our proposed routing methods in the IP and optical layers. Simulation studies are conducted to evaluate the performance of the proposed methods and the results are reported and discussed in Section 6.4. Section 6.5 concludes the chapter.

6.2 Network and Traffic Models

In the optical layer, the physical topology $G(V, E_p)$ is the interconnection of fibers and optical cross connects (OXC) where V is the set of N network nodes and E_p is the set of F fiber links. Each link is assumed to be of unit length and has W wavelengths of bandwidth C in each direction. In this chapter, all optical connections are assumed to be bi-directional, i.e. a connection reserving one wavelength in one fiber of a link, also reserves a wavelength in the fiber in the opposite direction. The architecture of a typical node in such an IP/MPLS over WDM network has been shown earlier in Fig. 2.7, where the OXC is connected to a LSR (Label Switched Router) through a user network interface (UNI) and add/drop ports. We assume all the OXCs in the network to be capable of full wavelength conversion.

The electrical switching needed for multicast routing and traffic grooming will be provided by the LSR. The applications considered here are ones that require bidirectional multicasting as in virtual private networks, video-conferencing, and online multi-player games. The i^{th} sub-wavelength multicast request is modeled as a bandwidth guaranteed bidirectional multicast LSP request and is denoted by (s_i, M_i, b_i) . Here, the source node is s_i while the *destination node set* of the multicast LSP request is M_i ; in our simulations studies reported later, these are randomly selected from the nodes in the network. Let n_i ($n_i \geq 0$) denote the number of destination nodes in the set M_i . A node belonging to $\{s_i\} \cup M_i$ is referred to as the member node of the multicast request. The bandwidth of the multicast LSP request is represented by b_i ; in our subsequent simulations, this is taken to be a random variable, uniformly distributed in $[x_1C, x_2C]$, where $0 < x_1 \leq x_2 \leq 1$, and C is the capacity of a single

wavelength. We assume that the multicast LSP requests arrive to the overall network from a Poisson process with an average arrival rate λ and have exponentially distributed holding times with a mean value μ . In the following, this will be referred to as a *multicast request* which will have n_i connections with $n_i b_i$ as the total bandwidth requested. It may be noted that during actual operations, it may not be possible to satisfy all the connections requested by such a multicast request, i.e. n_i' ($n_i' \geq 0$) out of the n_i requests may be blocked.

The overall bandwidth-blocking ratio experienced by the arriving multicast requests is an important performance parameter which has been used by us to evaluate network performance. Computed over a sufficiently long observation interval, this is the ratio of the total bandwidth of the blocked connections and the total bandwidth requested by the multicast requests arriving in that interval. With n_i' ($n_i' \geq 0$) as the number of blocked destination nodes in the i^{th} multicast request, the bandwidth blocking ratio is given by the following.

$$P_b = \frac{\sum_i n_i' b_i}{\sum_i n_i b_i} \quad (6.1)$$

6.3 Construction of Multicast Trees

For a network under the overlay model, we propose the following algorithm for path calculations in the IP/MPLS and optical layers in order to construct multicast trees. For the multicast routing, we use the shortest path heuristic (SPH) algorithm suggested by Takahashi and Matsuyama [72], to find a multicast tree in the network.

At every step of this algorithm, let M' represent the set of nodes (out of M) for which we have not yet found paths for connecting them to the partial tree (i.e. the other $M - M'$ nodes have already been connected in a partial tree). We denote a partial tree T' to be a tree connecting a subset of the destination nodes to the source node. The node set of the partial tree is denoted by T' . If a node of set M' is the closest to the established partial tree T' , we refer to that node in M' and the corresponding node in the partial tree as **neighbor nodes**. The distance between nodes in the IP/MPLS layer is calculated using the routing method given in chapter 3. If we find more than one pair of such neighbor nodes at any stage, then the resultant ties are arbitrarily broken by randomly choosing any one of these pairs. The main idea is that at each step we connect a destination to the existing partial multicast tree with a minimum cost path where the minimum cost path is the shortest path from the destination to the partial multicast tree (connecting the neighbor nodes).

6.4 Multicast Traffic Grooming Algorithms

In this work, we consider the network to be centrally controlled where multicast requests are centrally processed, one at a time. It may be noted that, in practice, multiple multicast requests may simultaneously arrive at the network. However, we assume that these will be processed and routed, one at a time. We use (s, M, b) to denote a multicast request, where s is the source node, M is the destination node set, and b is the bandwidth needed for this multicast request. In the overlay model, neighbor nodes may be found either in the IP/MPLS layer or in the optical layer. In the IP/MPLS layer, let the distance between neighbor nodes be denoted by $\mathbf{D}(\mathbf{I})$. This

is actually done by first calculating all the shortest paths between nodes in M' and the nodes of T' and selecting the shortest of these as $\mathbf{D}(\mathbf{I})$. If there is no path between the nodes of M' and the nodes in T' in the IP/MPLS feasible topology, then we set $\mathbf{D}(\mathbf{I}) = \infty$. In a similar fashion, the distance between neighbor nodes in the optical layer is denoted by $\mathbf{D}(\mathbf{O})$. This may also be calculated in a similar fashion. It may be noted that if there is no path between the nodes of M' and nodes in T' in the optical layer, then we set $\mathbf{D}(\mathbf{O}) = \infty$. In the following, we propose two traffic grooming policies for multicast traffic.

We first present a basic algorithm using a simple *IP/MPLS layer first* policy [10] as *Algorithm 1*. For a new multicast request, Algorithm 1 first tries to connect multicast destination nodes in M' to the partial tree in the existing IP/MPLS layer. After trying every node in this fashion, we check if some nodes are still left in M' , i.e. the multicast request has only been partially fulfilled at this stage. The nodes of M' and the partially fulfilled multicast tree are then transferred to the optical layer where we now try to set up lightpaths so as to complete the rest of the multicast tree. Note that once a new lightpath is added, we again try to connect the remaining nodes in M' in the IP/MPLS layer before trying to add another lightpath in the optical layer. The details of *Algorithm 1* are summarized in the flow chart of Fig. 6.1.

Fig. 6.1 Flow chart of Algorithm 1

In multicast traffic grooming, the way in which a lightpath is set up will greatly impact the overall multicast blocking performance. In Algorithm 1, a lightpath can only be set up between the partial tree T' and the partial destination set M' in the optical layer. We subsequently propose incorporating the saturated cut method [22] to exploit the network topology information in the overlay model. This gives the optical layer more choices to set up lightpaths and would consequently lead to lower blocking probabilities of multicast requests.

Lightpaths can provide huge bandwidth for the IP/MPLS layer but the number of wavelengths and add/drop ports in the optical layer is limited. Traffic grooming policies which are able to exploit the entire topology information available in the overlay model will be better able to reduce blocking and improve lightpath establishment. As studied in Chapter 5, the saturated cut (SC) approach [22] can effectively improve the network blocking performance. As in the case of unicast traffic studied in Chapter 5, we here apply the saturated cut method in the overlay model for efficient lightpath setup and multicast traffic grooming. The objective here is to use the available wavelength resources wisely so as to minimize the bandwidth blocking probability.

As described in Chapter 5, the main idea of the saturated cut (SC) method is to identify a partition (or cut) of the nodes of the network into two sets X and $\bar{X}$ such that the two sets are least connected. As the connection request across the SC is more likely to be blocked, adding a link for the SC may reduce the high level of utilization across the cut and decrease the network-blocking ratio. In the following, we will apply the SC method to the dynamic multicast traffic grooming for decreasing the network blocking ratio.

When a multicast request (s, M, b) arrives at the network, we define the source island X and the destination islands $X_1, X_2 \dots X_m$ as in Fig. 6.2 where m is the number of destination islands. The source island X is a node set consisting of node s and nodes that can be connected to node s in the feasible topology V , where V consists of the shortest feasible lightpaths whose residual bandwidth is bigger than or equal to b .

Fig. 6.2 The illustration of saturated cuts

The destination island X_j is a node set including at least one node, say d_i , in M and nodes that can be connected to the node d_i in V . Such islands may be found using the *breadth-first algorithm* as in [54]. Clearly, $X \cap X_1 \cap \dots \cap X_m = \emptyset$. We call the cuts among $X, X_1, X_2, \dots, X_m$ as SCs for the multicast request (s, M, b) in the feasible topology V . If more than one island is found or a destination node cannot be connected to source node in V , the island information is transferred to the optical layer through the user network interface (UNI). In the optical layer, every island can be considered as a *super node*, so a multicast tree need to be set up for connecting the source super node and destination super nodes in order to complete the multicast service in the IP/MPLS layer. We call such a multicast tree as a *super tree*. The optical layer calculates the shortest path between super nodes by calculating the shortest paths from each node in one island to each node in another island and choosing the shortest one to connect the super nodes. We use the multicast algorithm described in Section 6.3 to construct the super tree. If the super tree cannot be completed, the destination nodes in the destination islands that cannot be connected will be blocked. The details of *Algorithm 2* are described in the flow chart of Fig. 6.3. The node set of the source island X that belongs to M is denoted by Y ($Y \subseteq X \cap M$).

The node set of the destination island X_k that belongs to M is denoted by Y_k ($Y_k \subseteq X_k \cap M$).

Fig. 6.3 Flow chart of Algorithm 2

6.5 Performance of the Multicast Traffic Grooming Algorithms

We studied our proposed algorithms for dynamic multicast traffic grooming through simulation studies using the typical NSF topology with 14 nodes and 21 links and the

COST239 topology with 11 nodes and 26 links as shown in Fig. 3.8 and Fig. 3.9, respectively. The average node degree in the NSF topology and COST239 topology are 3 and 4.72 respectively. The average fibre-hop distances between nodes in the two topologies are 2.14 and 1.56 respectively. Consequently, we can see that the COST239 topology has a higher average node degree and a shorter average node distance than the NSF topology, i.e. the NSF topology is “sparser” than the COST239 topology or, alternatively, that the COST239 topology is “denser” than NSF topology. For both topologies, we assume each fiber to have $W = 8$ wavelengths in each direction, where each wavelength channel has capacity C . We assume that multicast applications supported by the network ask for a bandwidth that is uniformly distributed between $0.05C$ and $0.4C$. To examine the effect of multicast group size on the network performance, we have fixed the number of destination nodes of multicast requests in the simulation studies, where the number of nodes in the destination node set is denoted by n . (Results are obtained for different choices of n to see the network performance as a function of the multicast group size. It may be noted that $n = 1$ is equivalent to a unicast situation.) Since the traffic is bidirectional, the effective arrival rate is 2λ and hence the traffic generated per node, normalized to the wavelength channel capacity C , is given by

$$\rho = \frac{(0.05C + 0.4C)}{2CN} 2\lambda\mu n = \frac{0.45\lambda\mu n}{N} \quad (6.2)$$

For the results reported here, every simulation run has been repeated 10 times with 500,000 LSP requests for every run, and results have been averaged. We have obtained 95% confidence intervals for all our results; however, they are so narrow that we omit them from the figures in order to improve readability. Although some

existing works [67][81-83] studied the multicast traffic grooming problem, they did not study dynamic traffic grooming problem under the same traffic and network module in this work. A meaningful comparison is not possible. In this chapter, we only compare the algorithm 1 and algorithm 2 by the simulation results.

Fig. 6.4 Bandwidth blocking ratio vs. traffic load ($n = 2$) for NSF network

Fig. 6.5 Bandwidth blocking ratio vs. traffic load ($n = 3$) for NSF network

Fig. 6.6 Bandwidth blocking ratio vs. traffic load ($n = 4$) for NSF network

Fig. 6.4, Fig. 6.5 and Fig. 6.6 show the network blocking performance in the NSF network when the number of destination nodes n is chosen to be 2, 3 and 4, respectively. It may be seen that *Algorithm 2* can achieve better blocking performance than *Algorithm 1* in all cases. Because the NSF network is a sparse network, there are comparatively fewer lightpath connection choices in the optical layer. As shown in Chapter 5, increasing the success ratio of lightpath establishment will improve the overall network performance. The saturated cut method can enhance the lightpath establishment capability of the sparse NSF network by providing more connection choices. It should be noted that $T' \cup M' \subseteq X \cup X_1 \cup \dots \cup X_m$. A lightpath can be set up between the partial super tree and a destination island in *Algorithm 2* if a lightpath can not be set up between the partial tree T' and the partial destination set M' in *Algorithm 1*. So the nodes in the islands or the partial tree can find paths to each other in the feasible virtual topology and the optical layer has at least the same lightpath establishment choices in *Algorithm 2* as in *Algorithm 1*. This is the main reason why *Algorithm 2* provides better blocking performance (i.e. less blocking) than *Algorithm*

1 in the NSF network. We also observe that as the number of destination nodes increases, the performance of *Algorithm 1* become closer to that of *Algorithm 2*. We find that the number of nodes in $X \cup X_1 \cup \dots \cup X_m$ in *Algorithm 2* tends to come closer to the number of nodes in $T' \cup M'$ in *Algorithm 1* as the value of n increases. When this happens, the advantage of using *Algorithm 2* with the saturated cut method will fade, as the optical layer may not have many more choices for establishing lightpaths in *Algorithm 2* than in *Algorithm 1*. As a result, the blocking performance of *Algorithm 2* will tend to come closer to that of *Algorithm 1*.

Fig. 6.7 Bandwidth blocking ratio vs. traffic load ($n = 2$) for COST239 network

Fig. 6.8 Bandwidth blocking ratio vs. traffic load ($n = 3$) for COST239 network

Fig. 6.9 Bandwidth blocking ratio vs. traffic load ($n = 4$) for COST239 network

On the other hand, Algorithm 2 constructs the super tree regardless the path distance between the source and destination nodes. This may result in a bigger tree that wastes more network resources. In the dense COST239 network with a short average node distance and rich connections, this may counteract the advantage of the saturated cut method in increasing the lightpath establishment choices. Fig. 6.7, Fig. 6.8 and Fig. 6.9 show the network blocking performance in the COST239 network when the number of destination nodes n is chosen to be 2, 3 and 4, respectively. It can be seen from these figures that, in this case, Algorithm 2 can consistently and significantly outperform Algorithm 1 only when $n=2$. When the number of destination nodes increases beyond 2, the network performance under Algorithm 2 comes closer to that under Algorithm 1 and can even be somewhat poorer. As an example, for the case where $n=3$, Fig. 6.8 shows that Algorithm 2 performs somewhat better than Algorithm 1 (i.e. less blocking) only when the normalized traffic load is greater than 1.6 erlangs. For larger n , such as $n=4$ in Fig. 6.9, Algorithm 2 can only provide a

marginal improvement over Algorithm 1 and that too only at much higher values of the normalized traffic load.

To evaluate the effect of the *Add/Drop Ratio* R , we examine the bandwidth-blocking ratio for the network when $n = 3$. Fig. 6.10 and Fig. 6.11 show the network blocking performance as a function of the add/drop ratio R for the NSF and COST239 networks, respectively. Based on the results of our previous chapters (Chapters 3 and 5), we expected to see a threshold value beyond which there would only be a marginal improvement in P_b with increasing R . However, Fig. 6.10 shows that this value in NSF network is $7/8$, that is bigger than the threshold value of the NSF network in the

Fig. 6.10 Bandwidth blocking ratio vs. add/drop ratio ($n = 3$, $\rho = 5$ Erlangs) for NSF network

Fig. 6.11 Bandwidth blocking ratio vs. add/drop ratio ($n = 3$, $\rho = 14.2$ Erlangs) for COST239 network

unicast case shown in Chapter 3 and 5. In Fig. 6.11, it is shown that the COST239 network has to use all the add/drop ports to achieve the best blocking performance. If we decrease the add/drop ratio below 1, the network blocking ratio increases substantially. This is because we do multicast in the IP/MPLS layer and use the optical layer as a unicast network. A multicast request in the IP/MPLS layer needs to employ LSRs as intermediate nodes to make copies of the upstream data packets and push them into the downstream links. In this way, a lot of add/drop ports have to be used for transmit data packets but not for transmit or receiving data packets.

6.6 Summary

This chapter addresses the problem of traffic grooming in IP/MPLS over WDM networks with dynamic multicast traffic. We present a basic algorithm using a simple *IP/MPLS layer first* policy [10] as Algorithm 1, in which a lightpath is triggered to be

set up if a destination node cannot be connected in the IP/MPLS layer. Once a new lightpath is added, the IP/MPLS layer will try to connect the other destination nodes based on the new virtual topology. By applying the saturated cut method on Algorithm 1, we get Algorithm 2. In this, we first find the SC between nodes in the multicast group. Then the optical layer will try to add shortest lightpaths to make the feasible topology connected for the multicast request. Finally, the tree generation algorithm is executed in the IP/MPLS layer. Simulations have been carried out on two typical networks, e.g. NSF and COST239 networks. The simulation results show that the use of the saturated cut method for handling multicast traffic grooming can improve the network performance significantly when the number of destination nodes is relatively small as compared to the total number of nodes in the network. It is also shown that the saturated cut method is much more effective for sparse networks such as the NSF network than for dense networks such as the COST239 network.

Chapter 7 Conclusions and Recommendations

Traffic grooming is an important issue in high capacity optical networks. In this thesis, we investigate the dynamic traffic-grooming problem in IP/MPLS over WDM networks. Our focus is to devise new traffic grooming policies to provide low blocking ratio in the IP/MPLS layer and give differentiated blocking ratios for multi-class of traffic. This thesis makes four new and useful contributions to the body of knowledge in the area of dynamic traffic grooming in IP/MPLS over WDM networks. This chapter summarizes the main results and contributions and suggests some new related problems that may be considered for future research.

7.1 Summary

Chapter 3 first studies the *congestion spreading* problem that may be caused by alternate routing in dynamic traffic grooming networks. Based on observations of this problem, a new path inflation control (PIC) policy is proposed and studied in this chapter which can reduce the spread of congestion in an IP/MPLS over WDM network. In the proposed PIC policy, we introduce a *path inflation index* (PII) parameter to estimate the degree of congestion in the network. If the value of this PII parameter exceeds a predefined threshold value, a new shorter lightpath will be set up to keep the degree of congestion in check and even to reduce it, if feasible. Two typical network topologies, e.g. NSF and COST239 networks, were examined under different traffic grooming policies. It is shown that by limiting the spread of

congestion in the network, the proposed PIC policy performs significantly better than the more conventional one-hop-first (OHF) and optical-layer-first (OLF) policies that have been traditionally used for traffic grooming.

Chapter 4 extends the path inflation control (PIC) strategy to provide differentiated blocking performance for different priority classes of traffic in IP/MPLS over WDM networks. The novelty of the main idea proposed for this is to block a low priority LSP request if it will make the PII value bigger than a predefined threshold value. Simulation results show that a network operated in this fashion can indeed provide differentiated services without significantly impairing the overall network blocking performance when the network's traffic load is high. Unfortunately, under light load conditions, even if the network has enough bandwidth to accept all traffic, this proposed differentiated service approach still blocks low priority traffic unnecessarily leading to some degradation in network performance that should be avoided. In consideration of this requirement, we introduce an *Average Path Usage Index* (APII) parameter to monitor the traffic load in the network. This is used in conjunction with the PII parameter to decide whether or not to block a low priority LSP request. We find that this can not only provide differentiated service when the traffic load is high but also gives significantly less blocking for the lower priority class LSP requests at light traffic Loads. The APII mechanism has also been extended to provide differentiated services for more than two classes of traffic. In order to effectively cope with dynamic traffic fluctuations in the network, we further modify the APII parameter so that it only uses information from relatively recent LSPs to measure the traffic load. Our simulation studies indicate that by incorporating this new APII index

in the proposed differentiated service approach, the IP over WDM network performs very well even when the traffic load fluctuates dynamically.

Even though the overlay model is simpler and more feasible to implement with current technology than the peer model, it was shown that the overlay model has lower efficiency than the peer model[38]. This is because the IP/MPLS layer and the optical layer in the overlay model do not share topology information as seamlessly as they would do in the peer model. The IP/MPLS layer in the overlay model can only transmit the topology modification information to the optical layer by triggering lightpath establishments. In Chapter 5, we propose the use of the *Saturated Cut* (SC) method to allow the system to exploit topology information in the IP/MPLS layer so that more choices for establishing lightpaths may be made available while handling an LSP routing request. We find that this method can further reduce the lightpath-blocking ratios thereby improving the overall network performance further. Two SC methods have been defined according to the available bandwidth and path lengths. These SC methods were applied in conjunction with the PIC policy for traffic grooming in IP/MPLS over WDM networks and their performance was studied for two typical network topologies – the NSF network and the COST239 network. For the relatively sparse NSF network, our simulations indicate that the SC methods can indeed improve the LSP request blocking ratios significantly. On the contrary, for the dense COST239 network, the optical layer already has a lot of alternate path choices available to it. Therefore, applying the SC method in the COST239 network does not improve network performance to the extent observed in the NSF network. Finally, a heuristic modification (*Partial SC* method) has also been presented which provides

almost the same level of performance as the full SC methods but with much lower computational complexity.

Multicasting (i.e. one-to-many or many-to-many communications) is expected to be an important feature in future networks. Chapter 6 addresses the problem of traffic grooming in IP/MPLS over WDM networks with dynamic multicast traffic. Two algorithms are proposed to route multicast requests in the IP/MPLS over WDM networks, and their performance is studied through simulations. It is shown that, even for handling multicast traffic grooming, using the saturated cut method can significantly improve network performance when the number of destination nodes is relatively smaller than the total number of nodes in the network.

7.2 Recommendations for Further Research

Dynamic traffic grooming in WDM networks is an important and exciting research area which is likely to become an important issue in the operation of future broadband networks. Though a number of traffic grooming approaches have been defined and investigated in different networking contexts recently [6-8, 11, 13, 17, 37], several exciting directions may still be proposed for handling this issue more efficiently and in more general contexts. In the following, we summarize some of these approaches, which may be considered for extending further the research reported by us in this thesis.

1. *To consider and investigate the multilayer protection issue in dynamic traffic grooming* - The migration of real-time and high-priority traffic to IP networks means that modern IP networks will increasingly carry mission-critical business data, and must therefore provide reliable transmission. Network reliability will therefore become an important issue in IP/MPLS over WDM networks. It may be noted that in IP/MPLS over WDM networks, both layers can provide protection for an LSP. In *IP/MPLS layer protection*, an LSP is protected by providing a link-disjoint backup LSP between its end nodes [73]. In the *optical layer protection*, an LSP is protected by provisioning backup lightpaths for each lightpath traversed by the LSP [74, 75]. These two protection schemes (i.e. at the WDM layer or the IP/MPLS layer) will have their respective advantages and disadvantages. Since the number of lightpaths in the optical layer is much smaller than the number of LSPs in the IP/MPLS layer, protection in the optical layer would need smaller number of states than protection in the IP/MPLS layer, and would consequentially be faster [73]. On the other hand, with per LSP protection approach, the IP/MPLS layer protection will probably be more bandwidth efficient. In future implementation, it may be important to combine both protection schemes appropriately so as to provide different protection solutions for different requirements so that overall network resource utilization is optimized.
2. *To study the IP/MPLS layer rerouting [76] methods in dynamic traffic grooming* - Because the virtual topology will change according to the traffic distribution in the IP/MPLS layer, the existing LSPs that have been routed

may not be optimum in the new virtual topology. Rerouting some inefficient LSP paths is important for evenly distributing the traffic according to the link state of the changing virtual topology, and releasing some unnecessary lightpaths. With the rerouting technology, we may tear down an inefficient lightpath before all the sub-wavelength connections in the lightpath are terminated. We can reroute such sub-wavelength connections into other lightpaths. Then the occupied wavelength can be released for future lightpath connection requests. How to define an inefficient lightpath and where the LSP requests will be moved need to be studied in future research.

3. *To study the traffic grooming problem under the delay constraint* - For real-time services, e.g. videoconference, network games, and etc., the delay constraint needs to be considered. In this case, the network links have to be weighted according to its actual length. If the queueing delay is comparable with the transmission delay, the label switched routers (LSRs) also need to be weighted according to their traffic load. New traffic grooming methods need to be developed for providing LSPs under the delay constraint while efficiently using the network resources.
4. *To study dynamic traffic grooming in the multicast case* - In our work, we have proposed two multicast traffic grooming policies and studied them using simulations. Ways of constructing a small tree in the IP/MPLS over WDM network needs to be studied further to reduce the network-blocking ratio. The delay constraint also needs to be considered in the real-time service scenario.

Bibliography

- [1] A. Odlyzko, "Internet growth: Myth and reality, use and abuse," www.dtc.umn.edu/~odlyzko/doc/internet.growth.myth.pdf.
- [2] S. Bigo, W. Idler, J.-C. Antona, G. Charlet, C. Simonneau, M. Gorleir, M. Molina, S. Borne, C. de Barros, P. Sillard, P. Tran, R. Dischler, W. Poehlmann, P. Nouchi, and Y. Frignac, "Transmission of 125 WDM channels at 42.7 Gbit/s (5 Tbit/s capacity) over 12*100 km of TeraLight TM Ultra fibre," in *Proc. Proceedings 27th European Conference on Optical Communication*, Amsterdam, Netherlands, Sep. 2001.
- [3] L. Wei, "China's optical network evolution," *The SPIE magazine of photonics technologies and applications*, pp. 22-25, May 2002.
- [4] B. Mukherjee, *Optical Communication Networks*. New York: McGraw-Hill, 1997.
- [5] S. Binetti, A. Bragheri, E. Iannone, and F. Bentivoglio, "Mesh and multi-ring optical networks for long-haul applications," *IEEE/OSA Journal of Lightwave Technology*, vol. 18, pp. 1677-1684, Dec. 2000.
- [6] R. Dutta and G. N. Rouskas, "Traffic grooming in WDM networks: Past and future," *IEEE Network*, vol. 16, pp. 46-56, Nov-Dec 2002.
- [7] K. Y. Zhu and B. Mukherjee, "Traffic grooming in an optical WDM mesh network," *IEEE Journal on Selected Areas in Communications*, vol. 20, pp. 122-133, Jan. 2002.
- [8] H. Y. Zhu, H. Zang, K. Y. Zhu, and B. Mukherjee, "A novel generic graph model for traffic grooming in heterogeneous WDM mesh networks," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 285-299, Apr. 2003.
- [9] K. Y. Zhu, H. Zang, and B. Mukherjee, "A comprehensive study on next-generation optical grooming switches," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1173-1186, Sep. 2003.
- [10] X. M. Niu, W. D. Zhong, G. X. Shen, and T. H. Cheng, "Connection establishment of label switched paths in IP/MPLS over optical networks," *Photonic Network Communications*, vol. 6, pp. 33-41, July 2003.
- [11] E. Modiano and P. J. Lin, "Traffic grooming in WDM networks," *IEEE Communications Magazine*, vol. 39, pp. 124-129, Jul. 2001.
- [12] X. J. Zhang and C. M. Qiao, "On scheduling all-to-all personalized connections and cost-effective designs in WDM rings," *IEEE/ACM Transactions on Networking*, vol. 7, pp. 435-445, Jun. 1999.

- [13] A. L. Chiu and E. H. Modiano, "Traffic grooming algorithms for reducing electronic multiplexing costs in WDM ring networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 18, pp. 2-12, Jan. 2000.
- [14] J. Wang, W. H. Cho, V. R. Vemuri, and B. Mukherjee, "Improved approaches for cost-effective traffic grooming in WDM ring networks: ILP formulations and single-hop and multihop connections," *IEEE/OSA Journal of Lightwave Technology*, vol. 19, pp. 1645-1653, Nov. 2001.
- [15] P. J. Wan, G. Calinescu, L. W. Liu, and O. Frieder, "Grooming of arbitrary traffic in SONET/WDM BLSRs," *IEEE Journal on Selected Areas in Communications*, vol. 18, pp. 1995-2003, Oct. 2000.
- [16] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, "Some principles for designing a wide-area WDM optical network," *IEEE/ACM Transactions on Networking*, vol. 4, pp. 684-696, Oct. 1996.
- [17] D. Banerjee and B. Mukherjee, "Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study," *IEEE/ACM Transactions on Networking*, vol. 8, pp. 598-607, Oct. 2000.
- [18] A. E. Gencata and B. Mukherjee, "Virtual-topology adaptation for WDM mesh networks under dynamic traffic," *IEEE/ACM Transactions on Networking*, vol. 11, pp. 236-247, Apr. 2003.
- [19] A. Iselt, A. Kirstadter, and R. Chahine, "Bandwidth trading - A business case for ASON?," in *Proc. NETWORKS*, June 2004.
- [20] K. Sohraby, Z. S. Zhang, X. W. Chu, and B. Li, "Resource management in an integrated optical network," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1052-1062, Sep. 2003.
- [21] F. P. Kelly, "Network routing," *Philosophical Transactions of the Royal Society*, vol. A337, pp. 343-367, 1991.
- [22] D. Bertsekas and R. Gallager, *Data Networks*. New Jersey: Prentice Hall, 1991.
- [23] P. De Dobbelaere, K. Falta, L. Fan, S. Gloeckner, and S. Patra, "Digital MEMS for optical switching," *IEEE Communications Magazine*, vol. 40, pp. 88-95, Mar. 2002.
- [24] K. E. Stubkjaer, A. Kloch, P. B. Hansen, H. N. Poulsen, D. Wolfson, K. S. Jepsen, A. T. Clausen, E. Limal, and A. Buxens, "Wavelength converter technology," *IEICE Transactions on Communications*, vol. E82B, pp. 390-400, FEB 1999.
- [25] P. B. Chu, S. S. Lee, and S. Park, "MEMS: The path to large optical crossconnects," *IEEE Communications Magazine*, vol. 40, pp. 80-87, Mar 2002.
- [26] Q. Zheng and G. Mohan, "Protection approaches for dynamic traffic in IP/MPLS-over-WDM networks," *IEEE Communications Magazine*, vol. 41, pp. 24-29, May 2003.
- [27] E. Rosen, A. Viswanathan, and R. Callon, "Multiprotocol Label Switching Architecture," <http://www.faqs.org/rfcs/rfc3031.html>, IETF RFC 3031, 2001.

- [28] D. Awduche, L. Berger, D. Gan, T. Li, V. Srinivasan, and G. Swallow, "RSVP-TE: Extensions to RSVP for LSP Tunnels," <http://rfc3209.x42.com/>, IETF RFC 3209, Dec. 2001.
- [29] B. Jamoussi, "Constraint based LSP setup using LDP," www.faqs.org/rfcs/rfc3212.html, IETF RFC 3212, Jan. 2002.
- [30] O. Younis and S. Fahmy, "Constraint-Based Routing in the Internet: Basic Principles and Recent Research," *IEEE Communications Surveys and Tutorials*, vol. 5, pp. 2-13, Jan. 2003.
- [31] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications - an Approach to High Bandwidth Optical Wans," *IEEE Transactions on Communications*, vol. 40, pp. 1171-1182, July 1992.
- [32] R. Ramaswami and K. N. Sivarajan, "Design of logical topologies for wavelength-routed optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 840-851, Jun. 1996.
- [33] R. M. Krishnaswamy and K. N. Sivarajan, "Design of logical topologies: A linear formulation or wavelength-routed optical networks with no wavelength changers," *IEEE/ACM Transactions on Networking*, vol. 9, pp. 186-198, Apr. 2001.
- [34] J. F. P. Labourdette and A. S. Acampora, "logically rearrangeable multihop lightwave networks," *IEEE Transactions on Communications*, vol. 39, pp. 1223-1230, Aug. 1991.
- [35] "User Network Interface (UNI) 1.0 signaling specification," OIF2000.125.3, Dec. 2000.
- [36] D. Papadimitriou, J. Drake, J. Ash, A. Farrel, and L. Ong, "Requirements for Generalized MPLS (GMPLS) Signaling Usage and Extensions for Automatically Switched Optical Network (ASON)," <http://www.faqs.org/rfcs/rfc4139.html>, IETF RFC 4139, Jul. 2005.
- [37] C. S. Xin, C. M. Qiao, and S. Dixit, "Traffic grooming in mesh WDM optical networks - Performance analysis," *IEEE Journal on Selected Areas in Communications*, vol. 22, pp. 1658-1669, Nov. 2004.
- [38] W. D. Zhong, X. M. Niu, B. Chen, and S. K. Bose, "Performance comparison of overlay and peer models in IP/MPLS over optical networks," *Photonic Network Communications*, vol. 9, pp. 121-131, Jan. 2005.
- [39] H. Zhu, H. Zang, K. Zhu, and B. Mukherjee, "Dynamic traffic grooming in WDM mesh networks using a novel graph model," in *Proc. GLOBECOM'02 - IEEE Global Telecommunications Conference*, Nov 17-21 2002, Taipei, Taiwan2002.
- [40] B. Rajagopalan, J. Luciani, and D. Awduche, "IP over Optical Networks: A Framework," RFC 3717 Mar. 2004.
- [41] K. Kompella and Y. Rekhter, "OSPF Extensions in Support of Generalized MPLS," Work in Progress.
- [42] D. Awduche and Y. Rekhter, "Multiprotocol lambda switching: Combining MPLS traffic engineering control with optical crossconnects," *IEEE Communications Magazine*, vol. 39, pp. 111-116, MAR 2001.

-
- [43] C. Cavazzoni, V. Barosco, A. D'Alessandro, A. Manzalini, S. Milani, G. Ricucci, R. Morro, R. Geerdsen, U. Hartmer, G. Lehr, U. Pauluhn, S. Wevering, D. Pendarakis, N. Wauters, R. Gigantino, J. P. Vasseur, K. Shimano, G. Monari, and A. Salvioni, "The IP/MPLS over ASON/GMPLS test bed of the IST project LION," *IEEE/OSA Journal of Lightwave Technology*, vol. 21, pp. 2791-2803, Nov. 2003.
 - [44] D. O. Awduche, "MPLS and traffic engineering in IP networks," *IEEE Communications Magazine*, vol. 37, pp. 42-47, Dec. 1999.
 - [45] H. Zang, J. P. Jue, and B. Mukherjee, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks," *Optical Network Magazine*, vol. 1, pp. 47-60, Jan. 2000.
 - [46] C. Assi, A. Shami, M. A. Ali, Y. H. Ye, and S. Dixit, "Integrated routing algorithms for provisioning "sub-wavelength" connections in IP-over-WDM networks," *Photonic Network Communications*, vol. 4, pp. 377-390, July 2002.
 - [47] M. Kodialam and T. V. Lakshman, "Integrated dynamic IP and wavelength routing in IP over WDM networks," in *Proc. 20th Annual Joint Conference on the IEEE Computer and Communications Societies (IEEE INFOCOM 2001)*, Apr 22-26 2001, Anchorage, AK2001.
 - [48] R. Ramaswami, "Optical fiber communication: From transmission to networking," *IEEE Communications Magazine*, pp. 138-147, May 2002.
 - [49] H. Huang and J. A. Copeland, "Optical networks with hybrid routing," *IEEE Journal on Selected Areas in Communications*, vol. 21, pp. 1063-1070, Sept. 2003.
 - [50] S. K. Bose, B. Popat, Y. N. Singh, and A. N. V. B. Raju, "Sparse converter placement in WDM networks and their dynamic operation using path-metric based algorithms," in *Proc. ICC 2002*, New York, NY, Apr. 2002.
 - [51] G. X. Shen, S. K. Bose, T. H. Cheng, C. Lu, and T. Y. Chai, "Operation of WDM networks with different wavelength conversion capabilities," *IEEE Communications Letters*, vol. 4, pp. 239-241, July 2000.
 - [52] H. Zang, J. P. Jue, L. Sahasrabudhe, R. Ramamurthy, and B. Mukherjee, "Dynamic lightpath establishment in wavelength-routed WDM networks," *IEEE Communications Magazine*, vol. 39, pp. 100-108, Sep. 2001.
 - [53] L. Li and A. K. Somani, "Dynamic wavelength routing using congestion and neighborhood information," *IEEE/ACM Transactions on Networking*, vol. 7, pp. 779-786, Oct. 1999.
 - [54] J. V. Leeuwen, *Algorithms and complexity*: Elsevier, 1990.
 - [55] H. Harai, M. Murata, and H. Miyahara, "Performance of alternate routing methods in all-optical switching networks," in *Proc. INFOCOM '97*.1997.
 - [56] R. Lao and R. Killey, "Impact of Wavelength Routed Network Physical Topology on Blocking Probability Using a Dynamic Traffic Growth Model," in *Proc. OECC2003*, Shanghai, P.R.China, July 2003.

- [57] C. de Laat, E. Radius, and S. Wallace, "The rationale of the current optical networking initiatives," *Future Generation Computer Systems*, vol. 19, pp. 999-1008, AUG 2003.
- [58] B. Hurley, C. Seidl, and W. Sewell, "A survey of dynamic routing methods for circuit-switched traffic," *IEEE Communications Magazine*, vol. 25, pp. 13 - 21, Sep. 1987.
- [59] D. Mitra and J. B. Seery, "Comparative Evaluations of Randomized and Dynamic Routing Strategies for Circuit-Switched Networks," *IEEE Transactions on Communications*, vol. 39, pp. 102-116, JAN 1991.
- [60] J. Boyle, V. Gill, A. Hannan, D. Cooper, D. Awduche, B. Christian, and W. S. Lai, "Applicability Statement for Traffic Engineering with MPLS," <http://www.rfc-archive.org/getrfc.php?rfc=3346>, IETE RFC 3346, August 2002.
- [61] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss, "An Architecture for Differentiated Services," IETF RFC 2475, 1998.
- [62] G. X. Xiao, Y. W. Leung, and K. W. Hung, "Two-stage cut saturation algorithm for designing all-optical networks," *IEEE Transactions on Communications*, vol. 49, pp. 1102-1115, June 2001.
- [63] B. Chen, W. D. Zhong, and S. K. Bose, "A path inflation control strategy for dynamic traffic grooming in IP/MPLS over WDM network," *IEEE Communications Letters*, vol. 8, pp. 680-682, Nov. 2004.
- [64] R. A. Barry and P. A. Humblet, "Models of blocking probability in all-optical networks with and without wavelength changers," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 858-867, June 1996.
- [65] H. Harai, M. Murata, and H. Miyahara, "Performance of alternate routing methods in all-optical switching networks," in *Proc. Infocom*, 1997.
- [66] L. H. Sahasrabuddhe and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," *IEEE Communications Magazine*, vol. 37, pp. 67-73, Feb. 1999.
- [67] M. Ali and J. S. Deogun, "Cost-effective implementation of multicasting in wavelength-routed networks," *Journal of Lightwave Technology*, vol. 18, pp. 1628-1638, Dec. 2000.
- [68] Y. Y. Yang, J. C. Wang, and C. M. Qiao, "Nonblocking WDM multicast switching networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 11, pp. 1274-1287, Dec. 2000.
- [69] G. V. Chowdhary and C. S. R. Murthy, "Grooming of multicast sessions in WDM mesh networks," in *Proc. First Annual International Conference on Broadband Networks*, San Jose, California, Oct. 2004.
- [70] W. Sun, Y. Jin, W. Hu, H. He, X. Luo, P. Hu, W. Guo, Y. Su, and L. Leng, "Prototype Demonstration of IP Multicasting over optical networks with dynamic point-to-multipoint configuration.," in *Proc. OFC2005*.
- [71] J.-H. Cui, J. Kim, D. Maggiorini, K. Boussetta, and M. Gerla, "Aggregated Multicast --- A Comparative Study," in *Proc. Networking*, Pisa, Italy, May 2002.

- [72] H. Takahashi and A. Matsuyama, "An approximate solution for the steiner problem in graphs," *Math. Jap.*, vol. 24, pp. 573-577, 1980.
- [73] C. C. Huang, V. Sharma, K. Owens, and S. Makam, "Building reliable MPLS networks using a path protection mechanism," *IEEE Communications Magazine*, vol. 40, pp. 156-162, Mar. 2002.
- [74] S. Ramamurthy, L. Sahasrabudde, and B. Mukherjee, "Survivable WDM mesh networks," *Journal of Lightwave Technology*, vol. 21, pp. 870-883, Apr. 2003.
- [75] P. Demeester, M. Gryseels, A. Autenrieth, C. Brianza, L. Castagna, G. Signorelli, R. Clemente, M. Ravera, A. Jajszczyk, D. Janukowicz, K. Van Doorselaere, and Y. Harada, "Resilience in multilayer networks," *IEEE Communications Magazine*, vol. 37, pp. 70-76, Aug. 1999.
- [76] J. Ash, Y. Lee, P. Ashwood-Smith, B. Jamoussi, D. Fedyk, D. Skalecki, and L. Li, "LSP Modification Using CR-LDP," <http://www.rfc-archive.org/getrfc.php?rfc=3214>, IETF RFC 3214, Jan. 2002.
- [77] R. S. Tucker, "Peta bit per second routers: Optical vs. electronic implements, " proceeding of OFC 2006, Anaheim, CA, March 2006.
- [78] N. Golmie, T. D. Ndousse, and D. H. Su, "A Differentiated Optical Services Model for WDM Networks", *IEEE Communications Magazine*, pp. 68~73, Feb. 2000.
- [79] E. Salvadori and R. Battiti, "Quality of service in IP over WDM: considering both service differentiation and transmission quality", in *Proc. ICC*, June 2004.
- [80] R. Ul-Mustafa and A.E. Kamal, "On the grooming of multicast traffic in WDM networks" In *Proc. Ninth International Symposium on Computers and Communications*, July 2004.
- [81] A. Khalil, C. Assi, A. Hadjiantonis, Gellinas, N. AbdellatiQ and M. A. Alit, "On multicast traffic grooming in WDM networks", in *Proc. Ninth International Symposium on Computers and Communications*, July 2004.
- [82] X. Huang, F. Farahmand, and J. P. Jue, "Multicast traffic grooming in wavelength-routed WDM mesh networks using dynamically changing light-trees", *Journal of Lightwave Technology*, vol. 23, pp 3178-3187, Oct. 2005.

Author's Publications Related to This Thesis

Journal Papers:

- [1] Bin Chen, Wen-De Zhong and Sanjay Kumar Bose, "A path inflation control strategy for dynamic traffic grooming in IP/MPLS over WDM network," *IEEE Communications Letters*, vol.8, no. 11, Nov. 2004. (related to Chapter 3)

- [2] Wen-De Zhong, Xiaomei Niu, Bin Chen, S. K. Bose and Yaohui Jin, "Performance Comparison of overlay and peer models in IP/MPLS over Optical networks," *Photonic Network Communications*, 9:1, pp121-131, Jan 2005.

- [3] Bin Chen, S. K. Bose, W. D. Zhong, "Priority Enabled Dynamic Traffic Grooming," *IEEE Communications Letters*, vol. 9, no. 4, pp 366-368, Apr. 2005. (related to Chapter 4)

- [4] Bin Chen, Wen-De Zhong and Sanjay Kumar Bose, "Applying saturated cut method for dynamic traffic grooming in IP/MPLS over WDM networks," *IEEE Communications Letters*, vol. 10, no. 2, pp117-119, Feb. 2006. (related to Chapter 5)

- [5] Bin Chen, Wen-De Zhong and Sanjay Kumar Bose, "Providing differentiated service for multi-class traffic in IP/MPLS over WDM networks," submitted to *Photonic Network Communications*.

Conference Papers:

- [1] Bin Chen, W. D. Zhong, and S. K. Bose, "A path inflation control strategy for dynamic traffic grooming in IP/MPLS over WDM network," Proceeding of OECC/COIN'04 , Yokohama, Japan, July 2004.(This paper is awarded the IEEE Lasers and Electro-Optics Society (LEOs) Japan Chapter Young Scientist Award) (related to Chapter 3)

- [2] Bin Chen, S. K. Bose and W. D. Zhong, "Providing differentiated service for dynamic traffic grooming in IP/MPLS over WDM networks," Proceeding of ICOCN, Hongkong, Dec. 2004. (related to Chapter 4)

- [3] S. K. Bose, W. D. Zhong and Bin Chen, "Traffic grooming strategies for IP/MPLS over WDM networks," *Invited Paper*, Proceeding of COIN2005, Chongqing, June. 2005 (related to Chapter 3 and 4)

- [4] Bin Chen, W. D. Zhong, and S. K. Bose, "Dynamic multicast traffic grooming in IP/MPLS over WDM mesh networks," Proceeding of COIN2005, Chongqing, June. 2005 (related to Chapter 6)

- [5] Bin Chen, W. D. Zhong and S. K. Bose, "Enhancement of lightpath establishment capability for dynamic traffic grooming," Proceeding of European Conference on Optical Communication 2005 (ECOC 2005), Glasgow, Scotland, Sep. 2005. (related to Chapter 5)

- [6] Bin Chen, S. K. Bose and W. D. Zhong, "Applying saturated cut method in dynamic multicast traffic grooming in IP/MPLS over WDM mesh networks," Proceeding of ICICS2005, Bangkok, Dec. 2005. (related to Chapter 6)