

# **Multicast Protection and Energy Efficient Traffic Grooming in Optical Wavelength Routing Networks**

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## Abstract

This thesis has addressed two important networking aspects of optical wavelength routing networks, namely, multicast protection and energy-efficient traffic grooming. Both of them are investigated with respect to the time characteristics of the traffic and thus the network resources can be further optimized both in space and time.

### **Multicast Protection in Optical Wavelength Routing Networks under Scheduled Traffic**

Provisioning survivable multicast sessions in wavelength-routing optical networks has already been studied under static or dynamic traffic. However, in many practical cases, customers tend to require a large bandwidth at a specified time interval. Scheduled traffic model, in which the setup and teardown times are known in advance or vary in a specified larger time window, is more appropriate to characterize this kind of traffic. In this thesis, two scheduled traffic models are formulated and investigated for multicast protection in wavelength-routing optical networks, namely, Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM). With the guaranteed 100% restorability against any single link failure, the FSTM formulation can achieve a global minimum cost for establishing all multicast sessions. A two-step optimization approach is further proposed to deal with the survivable multicast provisioning problem under SSTM. By optimizing the network resources jointly in space and time, survivable multicast

sessions can be provisioned at much lower costs.

## **Energy-Efficient Traffic Grooming in Dynamic Optical Wavelength Routing Networks**

The energy consumption of the backbone network is quickly growing with the traffic and has aroused much concern from the research community. Recently, much research efforts have been paid to the topic of “Green Networking”, in which energy-efficient design of communication networks is the key objective, due to the huge economic cost and relevant environmental impacts.

Traffic grooming can make efficient use of the optical network bandwidth. This problem in optical wavelength routing network has been extensively studied with the aims to minimize the number of optical-electronic-optical conversions (OEOs), or maximize the total number of users served in the optical networks.

In the thesis, we investigate both static and dynamic traffic grooming problems in a wavelength routing network, so as to minimize the total energy consumption of the core network, with the additional consideration of the holding times of the light-paths and connection requests. In static case, all connection requests with their setup and tear-down times are known in advance, we formulate an Integer Linear Programming (ILP) to minimize the energy consumption. In dynamic case, we adopt a layered graph model called Grooming Graph and propose a new traffic grooming heuristics called Time-Aware Traffic Grooming (TATG) which takes the holding time of a new arrival connection request and the remaining holding time of existing light-paths into

consideration. We compare the energy efficiency of different traffic grooming policies under various traffic loads, and the results provide implications to choose the most energy-efficient traffic grooming policies under various scenarios.



# 摘要

本文试图解决两个重要的光网络组网的问题：多播保护以及节能流量疏导。我们从时间的角度对这两个问题进行分析，以达到资源在时间和空间上的双重优化。

## 在 scheduled traffic 下的多播保护问题：

在 scheduled traffic model 中，网络中的连接的建立时刻以及取消时刻是完全已知的，或者是已知在一定的时间范围滑动。这种模型更适合于网络中的多种应用。本文旨在讨论两种 scheduled traffic model 下的多播保护问题。两种模型分别叫做 Fixed Scheduled Traffic Model (FSTM)和 Sliding Scheduled Traffic Model (SSTM)。在 FSTM 中，我们提出的一种整数线性规划(ILP)，可以在保证 100% 恢复单个链路损坏的前提下，以最低的代价实现建立所有的多播连接。在 SSTM 中，我们运用两步优化的方法，可以实现网络资源在时间和空间上的双重优化。

## 节能流量疏导：

流量疏导可以充分利用光网络的巨大带宽资源。以往的研究集中在怎样减少网络中的光电光(OEO)转换或者怎样降低网络的阻塞率。本论文以降低能量的消耗为目标研究光网络的流量疏导。

本文从时间的角度出发，研究了静态流量疏导和动态流量疏导两方面的问题。在静态问题中，所有的网络连接以及他们的建立时刻和取消时刻都是提前知道的。我们提出了一种整数线性规划(ILP)，以实现能量消耗的最小化。在动态问题中，我们运用一种分层图实现了一种启发式算法 Time-Aware Traffic Grooming (TATG)并与其他常用的流量疏导策略做比较。比较结果对于在何种情形采用何种流量疏导策略具有指导性作用。

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# Chapter 1 Background

Nowadays, the traffic demand of Internet is under continuous and rapid growth. More and more bandwidth intensive applications, such as P2P video distribution, data intensive scientific computing, on-line game, etc, are emerging and gaining popularity. Optical networks adopting Wavelength Division Multiplexing (WDM) technology are considered to be the best choice for the backbone network of Internet. With WDM, a single fiber is capable of carrying up to hundreds of parallel optical wavelengths' transmission with each wavelength carrying 40 Gpbs. Wavelength routing means that an optical signal is optically switched to its intended terminal, while a light-path means an all-optical and end-to-end connection. We believe that wavelength routing equipments, namely, optical cross connects (OXC) and reconfigurable optical add-drop multiplexer (ROADM) will be in tremendous need in future. In the following of this chapter, we will introduce some important problems in optical WDM networks.

## 1.1 Routing and Wavelength Assignment

Routing and Wavelength Assignment (RWA) is a classical problem which is fundamental to solve many other important problems in optical networks including multicast routing, traffic grooming, protection and restoration, and virtual topology design. A light-path is established by selecting a route comprised of a sequence of fiber links and reserving a particular wavelength on each fiber link selected. Each

intermediate node in the light-path should provide optical by-pass facility to support the light-path. If there is no wavelength conversion capability in the intermediate node, the light-path is subject to wavelength continuity constraint which requires that the reserved wavelength should be the same in all the selected fiber links. The combination of the routing and wavelength assignment problems is referred to RWA problem which is usually very difficult. RWA problems can be further classified into two types: Static and Dynamic. In static case, the RWA problem is often referred to as static light-path establish (SLE) Problem in which a set of light-paths that need to be established is given in advance, along with some constraints on the number of wavelengths and/or wavelength continuity constraint. The objective of SLE problem is either to minimize network resources such as the number of wavelengths or the number of wavelength links in non-blocking scenario, or to maximize the number of light-paths to be established in blocking scenario. While the shortest path is often preferred for each individual light-path, we often have to sacrifice some light-paths to achieve a global optimum. The work in [24] shows that the SLE problem is NP-Complete. In dynamic case, the RWA problem is often referred to as dynamic light-path establishment (DLE) in which light-path request arrives one at a time and the network operator can look for a route and assign a wavelength to each light-path request separately. Simple heuristics are often employed to solve DLE problem. Usually, RWA problem is divided into two sub problems: routing and wavelength assignment. And they are tackled separately.



## 1.2 Survivability in Optical Networks

Different types of failures may occur in optical networks. Because optical networks carries huge amount of traffic, survivability in optical networks is extremely important. Fibers are usually put into cables. And each fiber carries up to hundreds of parallel optical wavelengths' transmission with each wavelength capable of carrying 10 Gbps data. A single link failure in optical networks can affect a large number of internet users and may bring disaster to some critical applications which require high-availability guarantees. In addition to link failures, node failures are also very common because of some catastrophic events happened at the locations of the OXCs such as the central office (CO). Since single link or node failures, where one failure is repaired before another failure is assumed to occur in the network, are the predominant form of failures in optical networks, most previous research works on survivability in WDM networks focused on the recovery from this kind of failure. Various approaches to support survivability in WDM networks exist which can be generally divided into protection and restoration techniques. Protection techniques use pre-assigned and extra bandwidth to assure survivability, which are also referred as proactive approaches. In contrast, restoration techniques reroute the affected traffic after a failure happens. In general, protection techniques can achieve faster recovery time but will cost more extra bandwidth. Restoration is more bandwidth efficient but it could not guarantee the success of recovery and the recovery time is much longer. Protection techniques can be further divided into link, segment and path protection. They can also be divided into dedicated and shared protection based

on whether the backup network resource is allowed to be shared by different traffic or not. Restoration techniques can also be divided into link, segment and path restoration.

Survivability can be provided in many layers in the network, e.g., ATM, IP, SONET, SDH, etc. The fault-management schemes in each layer have their own functionalities and characteristics. The optical layer can handle some faults more efficiently than the upper (client) layers and more desirable due to its advantages: speed, simplicity, effectiveness, and transparency.

### **1.3 Optical Multicasting**

Multicasting over a WDM optical network is an efficient means to deliver many popular applications such as video-on-demand, interactive distance learning, etc., which require point-to-multipoint connections. The concept of light-path has been extended to light-tree in [1]. A light-tree is a point-to-multipoint optical channel which may span multiple fiber links. Hence, a light-tree enables "single-hop" communication between a "source" node and a set of "destination" nodes [39]. To support multicast, the optical switching nodes must be multicast capable (MC) and have the ability to duplicate an input signal to several output signals. This capability of duplication can be realized in optical domain where power splitters are needed or in electronic domain where electronic replicators are needed. The MC switch with power splitters is called transparent switch, while the one with electronic replicators is called opaque switch which has inherent capability of wavelength conversion.



Supporting multicast or light-tree at the optical layer of the backbone network has several advantages:

1. Optical multicast improves the performance by eliminating the need for the store-and-forward functions of packet-switched technology and electronic packet copying. It reduces delay and eliminates OEO bottleneck. Light splitting is quick and cheap.
2. It enhances the virtual connectivity. The set of light-tree based virtual topologies is a superset of the set of light-path-based virtual topologies. A light-tree would enable a client node (e.g. IP router) to reach a larger number of other client nodes than would be allowed by its physical degree (i.e. number of transceivers). By using light-tree concept, a more general virtual topology can be formulated and the optical hardware cost (transceivers) is reduced. Bandwidth is also more efficiently used.
3. With the knowledge of the physical topology (optical layer), which may be different from that in upper layers, more efficient multicast routing is possible.

### **1.3.1 Routing and Wavelength Assignment of Optical Multicast**

It is well known that the optimal solution to point-to-point (Unicast) RWA is not practically achievable. With a more general construct (the light-tree) and hence a much larger search space, the Multicast Routing and Wavelength Assignment (RWA) problem is also NP-Complete.

## **Static Multicast RWA**

If the traffic patterns in the network are reasonably well known in advance and any traffic variations take place over long timescales, it is worthwhile to formulate Integer Linear Programming (ILP) to optimize the way in which network resources are assigned, even though optimization may require considerable computational effort. This case is called static multicast routing and wavelength assignment. In static optical multicast, a predetermined set of trees is computed to support the given multicast sessions. In this set of predetermined trees, there may be a single tree corresponding to a session (fixed routing), or there may be more than one tree (alternate routing) corresponding to a session. The current state of the network is not taken into consideration while computing the multicast trees.

## **Dynamic Multicast**

In the dynamic multicast, current utilization of the links is considered. When a multicast session request arrives, a route is checked for availability. If it is not available, then the request is blocked.

During dynamic and real-time network operation, Multicast RWA algorithm must be simple and fast. So a typical approach is to decouple the RWA problem into two separate sub-problems: the light-tree routing problem and the wavelength assignment problem.

Multicast routing problem is generalized to Steiner tree problem which is famous in Graph Theory and is known to be NP-complete. Steiner tree problem is often tackled

by two types of heuristics, namely Shortest Path based Heuristics (SPH) and Spanning Tree-based Heuristics (STH):

- Shortest Path-based Heuristic (SPH) [40]:

Assume we are given an undirected graph  $H(V, E)$  and a multicast group  $G = \{s, d_1, d_2, \dots, d_F\}$ . SPH starts with a tree  $MT = \{s\}$ , and the set of multicast group elements that have been included in the tree,  $Q = \{s\}$ . At each iteration, SPH chooses a destination  $d \in G - Q$ , which is closest to  $MT$ , extends  $MT$  by adding the minimum cost path from  $MT$  to  $d$ , and includes  $d$  in  $Q$ . The algorithm stops when  $Q = G$ .

- Spanning Tree-based Heuristic (STH) [40]:

This algorithm first constructs a closure graph of the multicast nodes from the original graph using the cost of the shortest path between each pair of members. A minimum spanning tree of the closure graph is obtained (in polynomial time), and then the shortest paths in the original graph are used to replace the edges of this minimum spanning tree. Finally, the multicast tree is obtained by removing any cycles.

Usually, after decoupling the multicast RWA problem into the two sub problems, wavelength assignment sub-problem is tackled by some similar heuristics as its unicast counterpart. Wavelength assignment is concerned with wavelength conversion and the number of wavelengths available. Two of the common used wavelength assignment heuristics are: First-Fit [39] and Random-Fit [39].



### 1.3.2 Current Research Topics about Optical Multicast

#### **Multicast Routing with Sparse Splitting:**

For WDM multicast, optical switches need to have the light splitting capability in order to make multiple replicas of an incoming bit stream which are then transmitted to the destination nodes. Switches with the splitting capability are usually much more expensive than those without. So in a practical network, one of the constraints is sparse splitting, which means that only a subset of the optical switches in a network supports light splitting. Previously proposed multicast tree formation algorithms, which assume that every node can split the incoming signals, are no longer feasible. Sparse splitting makes the multicast problem even more challenging.

In [25] and [27], several different heuristics were proposed to deal with the constrained multicast problem with sparse splitting:

- ✓ Member-Only Heuristics
- ✓ Member-First Heuristics
- ✓ Reroute-to-Source
- ✓ Reroute-to-Any
- ✓ Virtual Source Based Multicast Routing

In sparse splitting network, a light tree spanning all the members of a multicast session may not be found. The general idea of these heuristics is to establish light-forest which consists of one or more light trees. According to [25], among the



first four algorithms, Reroute-to-Source has resulted in the shortest delay; member-only required the least bandwidth; member-first required almost the same number of wavelengths as member-only, and achieved a slightly better trade-off between delay and bandwidth than reroute-to-any. In [27], the concept of “virtual source” was introduced, which meant a node having both the splitting and wavelength conversion capabilities. By exploiting the presence of virtual source nodes, the algorithm could achieve better performance in terms of the number of wavelengths required on a fiber and the amount of bandwidth consumed by the multicast forest.

### **Impairment-aware Multicast**

Physical layer impairments must be taken into account of routing optical connections especially multicast connections. In [40], the problem of constructing light trees under optical layer power budget constraints was investigated. This paper developed algorithms for building light trees to be as balanced as possible. However, this paper considered only power budget as the optical impairment. In [42], the same balancing techniques as in [40] were used to investigate the problem of multicast routing. This paper extended of the power budget impairment to Q-factor, which could involve more practical physical layer constraints such as dispersion, PMD, etc. In both [40] and [41], balanced algorithm was used which iteratively deleted the destination with worst signal quality and added it to the node with the best signal quality in the tree.

### **Multicast Protection**

Provisioning survivability in optical layer multicasting is also very important because a single failure in the tree structure may disrupt several downstream destinations and cause huge data loss. Singhal [2] studied protecting a single link failure using directed-link-disjoint backup trees. Unlike link-disjoint backup tree protection, the idea of directed-link-disjoint allowed the primary and the backup trees to share links but only in opposite directions. It was shown in [2] that a directed-link-disjoint backup tree could be successfully utilized to protect the multicast session against a single link failure and more bandwidth efficient than link-disjoint backup tree. In [3], Link, segment and path protection were proposed to provide survivability to multicast sessions. Extensions of link, segment or path protection were derived in [4-6]. P-cycle based link protection of multicast sessions was proposed in [7]. Generally speaking, segment and path protection can be more resource efficient than tree protection because path and segment protection can share bandwidth among primary tree and backup resources. However, tree protection can provide shorter restoration time as it uses 1+1 dedicated protection which needs no reconfiguration at intermediate nodes once a link failure happens.

## **1.4 Traffic Grooming**

In the previous sections, Both SLE and DLE problems assume that a connection requests the whole bandwidth of a wavelength. However, there is usually huge mismatch between the bandwidth of optics and electronics. Nowadays, the bandwidth of a light-path (or an optical wavelength channel) is 10 Gbps and



expected to grow to several hundreds Gbps. Actually, only a fraction of the customers are expected to have a need for such a high bandwidth. Many applications only require a bandwidth of OC-3, OC-12 and OC-48. So the problem becomes how to efficiently groom diverse low-speed connections onto high-capacity light-paths, which is known as traffic grooming problem. For example, in a mesh network, if multiple low-speed connections with different terminals are groomed onto a single light-path and we just want to terminate only one low-speed connection, we have to electronically terminate all the low-speed connections groomed onto this light-path and electronically route them. Usually, we would like to minimize the number of this kind of OEO conversion and electronic routing. Traffic grooming problem can also be classified into static and dynamic cases:

#### **1.4.1 Static Traffic Grooming**

In static case, all the connection requests of different bandwidth granularity (such as OC-1, OC-3, OC-12, OC-48, etc) are given in advance together with a network configuration (including physical topology, where each edge is a physical link, number of transceivers at each node, number of wavelengths on each fiber, and the capacity of each wavelength). We need to determine how to set up light-paths and groom the given connection requests onto them. In non blocking scenario, the objective of traffic grooming is to minimize the network cost such as the total number of OEO conversions, the number of used wavelength-links, while accommodating all the connection requests. In blocking scenario, where not all connections can be set up due to resource limitations, the objective is to maximize

the network throughput - the total amount of traffic to be served by the network. Static traffic grooming problem is also a generalization of SLE problem. So it is also NP-complete. According to [13], traffic grooming can be divided into four sub-problems, which are not necessarily independent: (1) determining the virtual topology that consists of light-paths, (2) routing the light-paths over the physical topology, (3) performing wavelength assignment to the light-paths, and (4) routing the traffic on the virtual topology. The virtual-topology design problem is NP-hard. In addition, routing and wavelength assignment is also NP-hard, as stated before. Therefore, traffic grooming in a mesh network is also a NP-hard problem. We can divide the whole traffic grooming problem into the four sub-problems, which there have been some previously established solutions to tackle separately. However, even if we get the optimal results for each of the four sub-problems, they are not necessarily independent and the solution may not be the optimal results to the whole problem.

With static traffic, the traffic grooming problem can be formulated as an integer linear programming (ILP) and the optimal solution can be obtained by solving the ILP. However, ILP is not scalable and solving the ILP for large networks is time prohibitive. So heuristics is needed. One way to make the problem tractable is to develop heuristic algorithms and jointly solve the grooming problem for one connection request at a time.



### 1.4.2 Dynamic Traffic Grooming

In dynamic traffic grooming, the connection request arrives one at a time, holds for a certain amount of time, and then departs from the network. The network operator deals with one connection request at a time and tries to minimize the operational cost to accommodate individual request, which implicitly attempts to minimize the blocking probability of future connection requests.

When a connection request arrives, the network operator should determine the following:

- (1) Should this connection be routed on the current set of light-paths, i.e. virtual topology, if it is possible.
- (2) How to change the virtual topology to accommodate the connection?

Different decisions on these two questions reflect the intentions of network operator, and are referred as Grooming Policies.

In [15], four different grooming policies are proposed:

- 1) Minimize the Number of Traffic Hops on the Virtual Topology (**MinTHV**)

This policy chooses the route with the fewest light-paths (Hops) for a connection.

- 2) Minimize the Number of Traffic Hops on the Physical Topology (**MinTHP**)

This policy chooses the route with the fewest fiber links for a connection.

- 3) Minimize the Number of Light-paths (**MinLP**)

This policy is similar to MinTHV but it tries to set up the minimal number of new light-paths to carry the traffic.

#### 4) Minimize the Number of Wavelength-Links (**MinWL**)

This policy is similar to MinTHP but it tries to consume the minimum number of extra wavelength-links, i.e., wavelength-links not being used by any light-paths for now, to carry the traffic.

In [15], a novel generic graph model was proposed to achieve these four traffic grooming policies by just modifying the weights of the edges in the graph model. In dynamic traffic grooming, the percentage of blocked traffic is a very important performance index. According to [15], MinTHV performed best when the transceivers were the more constrained resources and MinTHP gave the best results when the wavelength-links become more scarce resources.

Traffic grooming problem in optical wavelength routing network has been extensively studied with the aims to minimize the number of optical-electronic-optical conversions (OEOs), or maximize the total number of users served in the optical networks. Thus, the network bandwidth utilization can be optimized. In [13], a mathematical formulation of traffic grooming and several heuristics were proposed in order to improve the network throughput. In [14], a novel generic graph model was proposed to achieve various traffic grooming policies by just modifying the weights of the edges in the graph model. Both [13] and [14] dealt with static traffic grooming problem in which all connection requests were known in

advance. In [15], the novel generic graph model in [14] was applied to a dynamic traffic grooming problem in which connection requests arrived at the network randomly. In [16], a layered Grooming Graph was proposed to investigate the survivable traffic grooming algorithms. In [17], the holding time information of connections was exploited to improve the traffic grooming performance in terms of blocking probability. In [18], the traffic grooming problem was studied under a sliding scheduled traffic model in which the holding duration of connections could slide in a larger time window.

## **1.5 Contributions**

### **1.5.1 Multicast Protection with Scheduled Traffic Model**

In this thesis, while keeping the advantage of short restoration time, we have tried to increase the resource efficiency of directed-link-disjoint backup tree protection by optimizing the network resources jointly in space and time.

Most of the previous works on multicast protection considered either a static or dynamic traffic model, which might not well-characterize the applications that require bandwidth at a specific time interval. Network resources may be reserved by users in advance. For instance, a soccer game is usually broadcasted to audiences according to a predetermined timetable. Therefore, scheduled traffic model [8], in which the setup and tear-down times of the traffic demands are known in advance or vary in a specified larger time window, is a more proper traffic model for these kinds of applications. With the scheduled time information, network resources can be



further optimized both in space and time. The routing and wavelength assignment problem for survivable unicast scheduled traffic demands has been studied in [9-10].

In this thesis, we consider a set of multicast sessions with scheduled traffic. There are two kinds of scheduled traffic model: Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM). In this thesis, we first consider Routing and Wavelength Assignment (RWA) of survivable multicast sessions under FSTM. We provide integer linear programming (ILP) formulation to solve the multicast tree protection problem in a WDM optical network with scheduled traffic. Both wavelength-convertible and wavelength-continuity constrained cases are investigated. With the guaranteed 100% restorability against any single link failure, the formulation can achieve a global minimum cost for establishing all multicast sessions. Numerical experiments have indicated that the proposed ILP can achieve significant reduction in the cost for establishing all multicast sessions compared to the previous schemes which are unaware of the traffic time information, hence, better network resource optimization is realized. In order to deal with the problems under SSTM, a two-step optimization approach has been adopted. In the first step, each multicast request is optimally scheduled within its specified time window. In the second step, the problem is reduced to the FSTM problem and can be solved by our proposed ILPs for FSTM.

### **1.5.2 Energy Efficient Time-Aware Traffic Grooming**

Since traffic grooming requires electrical multiplexing and OEO conversion which

induce much energy consumption, recently, there is growing interest in achieving energy efficient traffic grooming. In [19], both MILP and heuristics were reported to solve the energy-minimized static traffic grooming problem for IP over WDM Networks. In [20], two different models of power consumption of optical networks were proposed: flow based formulation and interface based formulation. The work in [21] adopted the interface based formulation and formulated an Integer Linear Programming (ILP) for the traffic grooming problem with the objective of minimizing the power consumption. In [22] and [23], a more detailed energy consumption model considering the modular structure of optical network nodes was presented and a similar layered graph model to [14] was adopted to solve the dynamic traffic grooming problem.

As far as we know, existing works on energy-efficient traffic grooming do not consider a very important factor in energy saving – time, as energy consumption is the product of both power and time. Hence, minimizing the power consumption may not necessarily minimize the energy consumption. In this thesis, we have studied both static and dynamic traffic grooming problems with an additional consideration of time information. We have investigated both static and dynamic traffic grooming problems in a wavelength routing network, so as to minimize the total energy consumption of the core network, with the additional consideration of the holding times of the light-paths and connection requests. In static case, all connection requests with their setup and tear-down times are known in advance, we have formulated an Integer Linear Programming (ILP) to minimize the energy

consumption. In dynamic case, we adopt a layered graph model called Grooming Graph and propose a new traffic grooming heuristics called Time-Aware Traffic Grooming (TATG) which takes the holding time of a new arrival connection request and the remaining holding time of existing light-paths into consideration. We have compared the energy efficiency of different traffic grooming policies under various traffic loads, and the results provide implications to choose the most energy-efficient traffic grooming policies under various scenarios.

## 1.6 Organization of Thesis

**Chapter 2** discusses the multicast protection problem under both Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM).

**Chapter 3** discusses both static traffic grooming and dynamic traffic grooming problems to save energy consumption in optical networks, with additional consideration of requested holding times of connection requests and the remaining holding times of light-paths.

**Chapter 4** concludes this thesis and specifies the possible future research topics.



# **Chapter 2 Multicast Protection in WDM Optical Network with Scheduled Traffic**

## **2.1 Introduction**

Nowadays, provisioning of multicast sessions over a wavelength-routed WDM optical network is an efficient means to deliver many popular applications such as video-on-demand, interactive distance learning, etc., which require point-to-multipoint connections. The concept of light-path has been extended to light-tree in [1]. To support multicast, the optical branching nodes must be multicast capable (MC) and have the ability to duplicate an input signal to several output signals. This capability of duplication can be realized in either optical domain or electronic domain, where optical power splitters or electronic replicators are needed, respectively. The MC switch with power splitters is called transparent switch, while the one with electronic replicators is called opaque switch which has inherent capability of wavelength conversion. In this work, we consider both wavelength-convertible optical networks and wavelength-continuity constrained optical networks. To assure the service availability, it is imperative to protect the optical multicast sessions, since a single failure may disrupt several downstream destinations and lead to huge data loss.

Singhal [2] studied protecting a single link failure using directed-link-disjoint backup trees. Unlike link-disjoint backup tree protection, the idea of directed-link-disjoint allowed the primary and the backup trees to share links but only in opposite

directions. It has been shown in [2] that a directed-link-disjoint backup tree could be successfully utilized to protect the multicast sessions against a single link failure and was more bandwidth-efficient than a link-disjoint backup tree. In [3], link, segment and path protection were proposed to provide survivability to multicast sessions. Extensions of link, segment or path protection were further derived in [4-6]. P-cycle based link protection of multicast sessions was proposed in [7]. Generally speaking, segment and path protection can be more resource efficient than tree protection because path and segment protection can share bandwidth among primary tree and backup resources. However, tree protection can provide shorter restoration time, as it uses 1+1 dedicated protection which needs no reconfiguration at intermediate nodes once a link failure happens.

As mentioned in 1.5.1, most of the previous works on multicast protection considered either a static or dynamic traffic model, which may not well-characterize the applications that require bandwidth at a specific time interval. Network resources may be reserved by users in advance. For instance, a soccer game is usually broadcasted to audiences according to a predetermined timetable. Therefore, scheduled traffic model [8], in which the setup and tear-down times of the traffic demands are known in advance or vary in a specified larger time window, is a more proper traffic model for these kinds of applications. With the scheduled time information, network resources can be further optimized both in space and time. The routing and wavelength assignment problem (RWA) for survivable unicast scheduled traffic demands have been studied in [9-10]. In [11], multicast tree protection under



fixed scheduled traffic was studied and the results have shown that the cost for provisioning the survivable multicast sessions could be much lowered. Further investigations are discussed in this paper.

In this thesis, we consider a set of multicast sessions with scheduled traffic. Single link failure is assumed because of its predominance in optical networks. Two kinds of scheduled traffic model are considered, namely, Fixed Scheduled Traffic Model (FSTM) and Sliding Scheduled Traffic Model (SSTM). Under FSTM, a multicast session  $S_i$  is represented by  $\{s_i, (d_{i1}, d_{i2}, \dots, d_{ij}, \dots), (t_{is}, t_{ie})\}$ , where  $s_i$  is the source node and  $d_{ij}$  is the  $j$ th destination of the session  $S_i$ .  $t_{is}$  and  $t_{ie}$  are the exact setup and teardown times of  $S_i$ , respectively. Some customers do not need exact setup times, but need reserve the bandwidth within a time period. Like data transmissions during the night. SSTM is more appropriate for this case in which a multicast session  $S_i$  is represented by  $\{s_i, (d_{i1}, d_{i2}, \dots, d_{ij}, \dots), (t_{is}, t_{ie}), \tau_i\}$ , where  $t_{is} - t_{ie} \geq \tau_i \geq 0$ .  $s_i$  and  $d_{ij}$  have the same meanings as those under FSTM.  $(t_{is}, t_{ie})$  is a larger time window during which  $S_i$  must be provisioned and  $\tau_i$  is the holding time of  $S_i$ . So the multicast demand can slide within the larger time window  $(t_{is}, t_{ie})$ , which gives the service providers more flexibility to allocate the limited network resources to multiple traffic demands.

Based on the FSTM traffic model, an integer linear programming (ILP) formulation, namely *Multicast Tree Protection with Scheduled Traffic* (MTP-ST), is performed to solve the routing and wavelength assignment (RWA) of survivable multicast sessions in a WDM optical network. Both wavelength-convertible and wavelength-continuity



constrained cases are investigated. With the guaranteed 100% restorability against any single link failure, the formulation can achieve a global minimum cost for establishing all multicast sessions. Numerical experiments have indicated that the proposed MTP-ST formulation can achieve significant reduction in the cost for establishing all multicast sessions, compared to the previously proposed schemes which were unaware of the traffic time information. Hence, better network resource optimization is realized. In addition, in order to tackle the survivable multicast provisioning problem under SSTM traffic model, a two-step optimization approach similar to that in [10] is further adopted. First, each multicast request is optimally scheduled within its specified time window, such that the problem is reduced to FSTM, which is then solved using our proposed MTP-ST formulation, in the second step. In general our proposed approach can increase the resource efficiency of directed-link-disjoint backup tree protection by optimizing the network resources jointly in space and time, while keeping the advantage of short restoration time.

The remainder of this chapter is organized as follows. In Section 2.2, the ILP formulation for MTP-ST under Fixed Scheduled Traffic Model (FSTM) is presented. In Section 2.3, two numerical examples are studied and the results are discussed. In Section 2.4, a two-step optimization approach is proposed for MTP-ST under Sliding Scheduled Traffic Model (SSTM). Section 2.5 summarizes the chapter.

## **2.2 Multicast Protection under FSTM**

The inputs of the problem are listed as follows:

- ✓ The network topology  $G = (V, E)$  is given as a weighted undirected graph.  $V$  is the set of  $N$  multicast capable network nodes.  $E$  is the set of weighted links.
- ✓  $\omega_{m,n} = \omega_{n,m}$  is the cost of using one wavelength on the link between nodes  $m$  and  $n$ .
- ✓  $D_p(m)$  is the degree of node  $m$  and equals the number of fiber links connecting to node  $m$ .
- ✓  $W$  is the maximum number of wavelengths in each direction of a fiber link.
- ✓ A set of  $k$  primary multicast sessions (trees).  $P_i = 1$  or  $0$  indicating whether session  $S_i$  requires protection against single link failure or not, respectively. If the primary tree  $S_i$  requires protection, the backup tree for  $S_i$  is denoted as  $S_{i+k}$ . So there are totally  $2k$  trees at most.  $L_i$  is the number of destinations in the tree  $S_i$ .  $T_{i,j} = T_{j,i}$  is a Boolean, indicating whether tree  $S_i$  and tree  $S_j$  overlap in time ( $=1$ ) or not ( $=0$ ). For example, if the two time intervals  $(t_{is}, t_{ie})$  and  $(t_{js}, t_{je})$  overlap,  $T_{i,j} = 1$ . We also assume that each multicast session requires a full wavelength bandwidth.

The variables for the ILP are defined as follows:

- ✓ Boolean variable  $X_{m,n}^c$  indicates whether one or more multicast trees traverse the link from node  $m$  to  $n$  using wavelength  $c$  ( $=1$ ) or not ( $=0$ ).
- ✓ Boolean variable  $M_{m,n}^{i,c}$  indicates whether wavelength  $c$  on the link from node  $m$  to  $n$  is occupied by tree  $i$  ( $=1$ ) or not ( $=0$ ).

- ✓ Boolean variable  $V_p^i$  indicates whether node  $p$  belongs to tree  $i$  ( $=1$ ) or not ( $=0$ ).
- ✓ Integer commodity-flow variable  $F_{m,n}^i$  is the number of commodity flow units of tree  $i$  going through the link from node  $m$  to  $n$ . Each destination requires 1 unit of commodity.
- ✓ If there is no wavelength converter, Boolean variable  $C_c^i$  is needed which indicates whether tree  $i$  uses wavelength  $c$  ( $=1$ ) or not ( $=0$ ).

The objective of the ILP is:

$$\text{Minimize } \sum_{c=1}^{c=W} \sum_{m,n} \omega_{m,n} \cdot X_{m,n}^c \quad (2-1)$$

Subject to:

Tree creation constraints:

$$\forall i, \forall n \neq s_i : \sum_{m,c} M_{m,n}^{i,c} = V_n^i \quad (2-2)$$

$$\forall i : \sum_{m,c} M_{m,s_i}^{i,c} = 0 \quad (2-3)$$

$$\forall i, \forall j \in S_i : V_j^i = 1 \quad (2-4)$$

$$\forall i, \forall m \neq d_{ij}, j \geq 1 : \sum_{n,c} M_{m,n}^{i,c} \geq V_m^i \quad (2-5)$$



$$\forall i, m: \sum_{n,c} M_{m,n}^{i,c} \leq D_p(m) \cdot V_m^i \quad (2-6)$$

Commodity flow constraints:

$$\forall i, \forall m \notin S_i: \sum_n F_{m,n}^i = \sum_n F_{n,m}^i \quad (2-7)$$

$$\forall i, \forall m = s_i: \sum_n F_{s_i,n}^i = L_i \quad (2-8)$$

$$\forall i, \forall m = s_i: \sum_n F_{n,s_i}^i = 0 \quad (2-9)$$

$$\forall i, \forall m = d_{ij}, j \geq 1: \sum_n F_{n,m}^i = \sum_n F_{m,n}^i + 1 \quad (2-10)$$

$$\forall i, m, n: \sum_c M_{m,n}^{i,c} \leq F_{m,n}^i \quad (2-11)$$

$$\forall i, m, n: F_{m,n}^i \leq N \cdot \sum_c M_{m,n}^{i,c} \quad (2-12)$$

Directed link disjointness constraint:

$$\forall i = 1 \dots k, \forall m, n: \sum_c M_{m,n}^{i,c} + \sum_c M_{m,n}^{i+k,c} \leq 1 \quad (2-13)$$

Wavelength usage constraints:

$$\forall m, n, c: X_{m,n}^c \leq \sum_i M_{m,n}^{i,c} \quad (2-14)$$

$$\forall m, n, c: k \cdot X_{m,n}^c \geq \sum_i M_{m,n}^{i,c} \quad (2-15)$$

Time joint constraint:

$$\forall m, n, p, q (T_{p,q} = 1) : M_{m,n}^{p,c} + M_{m,n}^{q,c} \leq 1 \quad (2-16)$$

Wavelength-continuity constraints (when there is no wavelength converter)

$$\forall i : \sum_c C_c^i = 1 \quad (2-17)$$

$$\forall i, c, m, n (n > m) : M_{m,n}^{i,c} + M_{n,m}^{i,c} \leq C_c^i \quad (2-18)$$

Our formulation allows wavelength sharing by different trees which do not overlap in time, which is a special feature of the scheduled traffic model.

- ✓ The objective function (2-1) minimizes the total costs of establishing all multicast trees. It can be replaced by other objectives, such as minimizing the energy consumption.
- ✓ Equation (2-2) ensures that every node which belongs to a multicast session (except the source node) has one and only one incoming wavelength.
- ✓ Equation (2-3) ensures that the source node of each tree has no incoming wavelength.
- ✓ Equation (2-4) ensures that every source node and destination node of each multicast tree belong to the tree.
- ✓ Equation (2-5) ensures that every node (except the destination nodes) has at least one outgoing wavelength.

- ✓ Equation (2-6) ensures that the number of outgoing wavelengths of a node is limited by the degree of the node and every node with at least one outgoing wavelength belongs to the tree.

Equations (2-7) to (2-12) are flow-conservation equations:

- ✓ Equation (2-7) ensures that the incoming flow is the same as the outgoing flow for every node which is neither a source nor a destination.
- ✓ Equation (2-8) and (2-9) ensures that the outgoing flow and incoming flow of the source node are the number of the destinations in the tree and 0 respectively.
- ✓ Equation (2-10) ensures that the outgoing flow is one less than the incoming flow for destination nodes.
- ✓ Equation (2-11) ensures that the flow on each direction of a link is positive if one of the wavelengths on that direction of the link is occupied by the tree.
- ✓ Equation (2-12) ensures that there is no flow on each direction of a link it is not occupied by the tree.
- ✓ Equation (2-13) ensures that a primary tree and its protection tree can not share a link in the same direction.
- ✓ Equation (2-14) ensures that a wavelength on each direction of a link is occupied if one or more trees choose to use it.
- ✓ Equation (2-15) ensures that a wavelength on each direction of a link can be shared by  $k$  trees at most. This is because a primary tree and its backup cannot



share a wavelength in the same direction of each link.

- ✓ Equation (2-16) ensures that two trees cannot share a wavelength in the same direction of a link if they overlap in time.

Equation (2-17) and (2-18) are active only when wavelength-continuity constraints are applied:

- ✓ Equation (2-17) ensures that only one wavelength is chosen for a multicast tree.
- ✓ Equation (2-18) ensures that all links occupied by a tree are on the same wavelength and one tree can not occupy both directions of a link (avoiding the loop).

## 2.3 Illustrative Examples

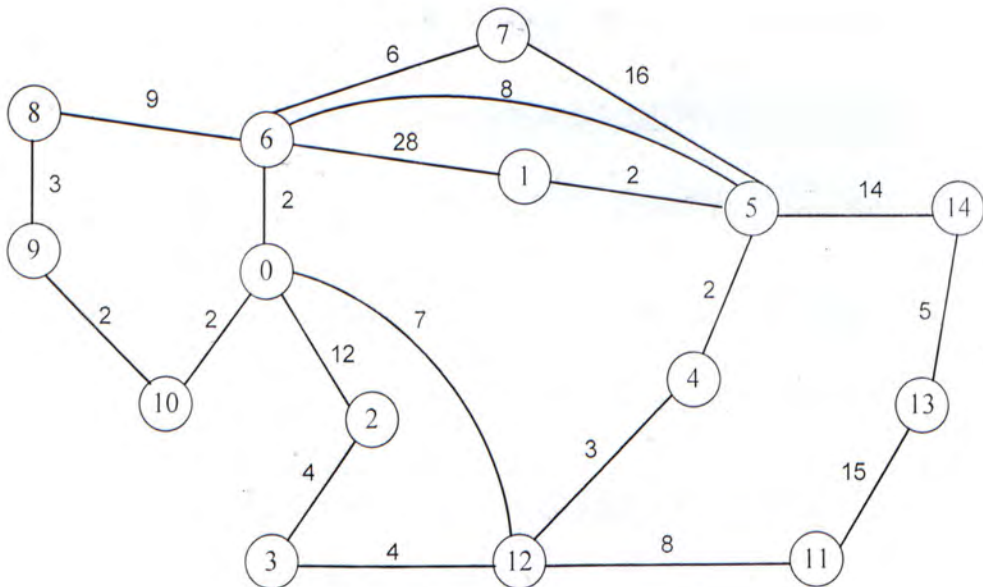


Fig. 2.1: Example 1: a 15-node network with bidirectional links

We employ the 15-node Pacific Bell network (shown in Fig. 2.1) for Example 1 and

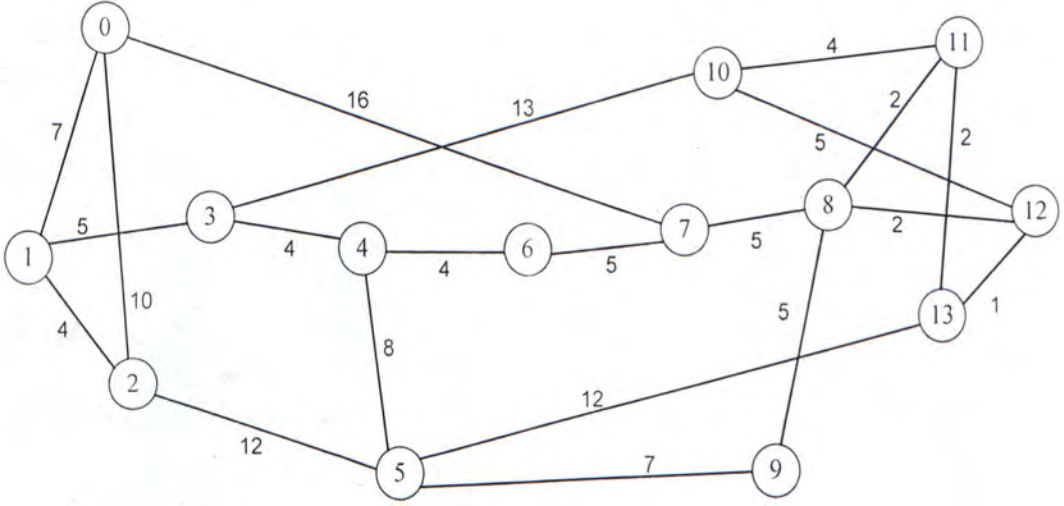


Fig. 2.2: Example 2: a 14-node NSFNET with bidirectional links

the 14-node NSFNET (shown in Fig. 2.2) for Example 2, respectively. Each link carries four wavelengths in both directions.

In Example 1, there are five primary multicast sessions ( $k=5$ ).  $\mathcal{S}_1 = \{0, (1, 2, 4, 5, 10, 11, 12, 13, 14), (t_{1s}, t_{1e})\}$ ,  $\mathcal{S}_2 = \{9, (1, 2, 3, 4, 5, 6, 10, 11), (t_{2s}, t_{2e})\}$ ,  $\mathcal{S}_3 = \{12, (0, 5, 8, 9, 10, 14), (t_{3s}, t_{3e})\}$ ,  $\mathcal{S}_4 = \{14, (1, 2, 3, 4), (t_{4s}, t_{4e})\}$ ,  $\mathcal{S}_5 = \{7, (0, 6), (t_{5s}, t_{5e})\}$ .  $t_{is}$  and  $t_{ie}$  are used as parameters to control the time overlap in our formulation. Only sessions  $\mathcal{S}_1$ ,  $\mathcal{S}_4$  and  $\mathcal{S}_5$  require single-link protection ( $P_1 = P_4 = P_5 = 1$ ). Each of them requires a backup tree  $\mathcal{S}_6$ ,  $\mathcal{S}_9$  and  $\mathcal{S}_{10}$ , respectively. These backup trees have the same setup and tear-down time as their corresponding primary trees. Time correlation parameter refers to the relative degree of time-overlap among the trees. In Example 1, time correlation parameter “High” means only  $T_{1(6),2} = T_{1(6),3} = T_{2,3} = T_{3,4(9)} = T_{3,5(10)} = T_{4(9),5(10)} = 1$ ; “Medium” means only  $T_{2,3} = T_{3,4(9)} = T_{3,5(10)} = T_{4(9),5(10)} = 1$ ; and “Low” means only  $T_{3,4(9)} = T_{3,5(10)} = 1$ . The indices in the subscript brackets refer to the respective backup trees.

In Example 2, we also adopt five primary sessions ( $k=5$ ).  $S_1 = \{0, (2, 3, 4, 6, 10, 11, 12, 13), (t_{1s}, t_{1e})\}$ ,  $S_2 = \{5, (0, 1, 2, 7, 8), (t_{2s}, t_{2e})\}$ ,  $S_3 = \{7, (3, 4, 5, 6), (t_{3s}, t_{3e})\}$ ,  $S_4 = \{11, (1, 2, 10, 13), (t_{4s}, t_{4e})\}$ ,  $S_5 = \{12, (8, 9, 10), (t_{5s}, t_{5e})\}$ . We assume that all of the five primary sessions require single-link protection ( $P_1 = P_2 = P_3 = P_4 = P_5 = 1$ ). So the corresponding backup trees for them are  $S_6, S_7, S_8, S_9$  and  $S_{10}$ , respectively. These backup trees have the same setup and tear-down time as their corresponding primary trees. In Example 2, time correlation parameter “High” means only  $T_{1(6),2(7)} = T_{1(6),3(8)} = T_{2(7),3(8)} = T_{3(8),4(9)} = T_{3(8),5(10)} = T_{4(9),5(10)} = 1$ ; “Medium” means only  $T_{2(7),3(8)} = T_{3(8),4(9)} = T_{3(8),5(10)} = T_{4(9),5(10)} = 1$ ; and “Low” means only  $T_{3(8),4(9)} = T_{3(8),5(10)} = 1$ .

The traffic patterns (number of requests, source and destinations of each request,

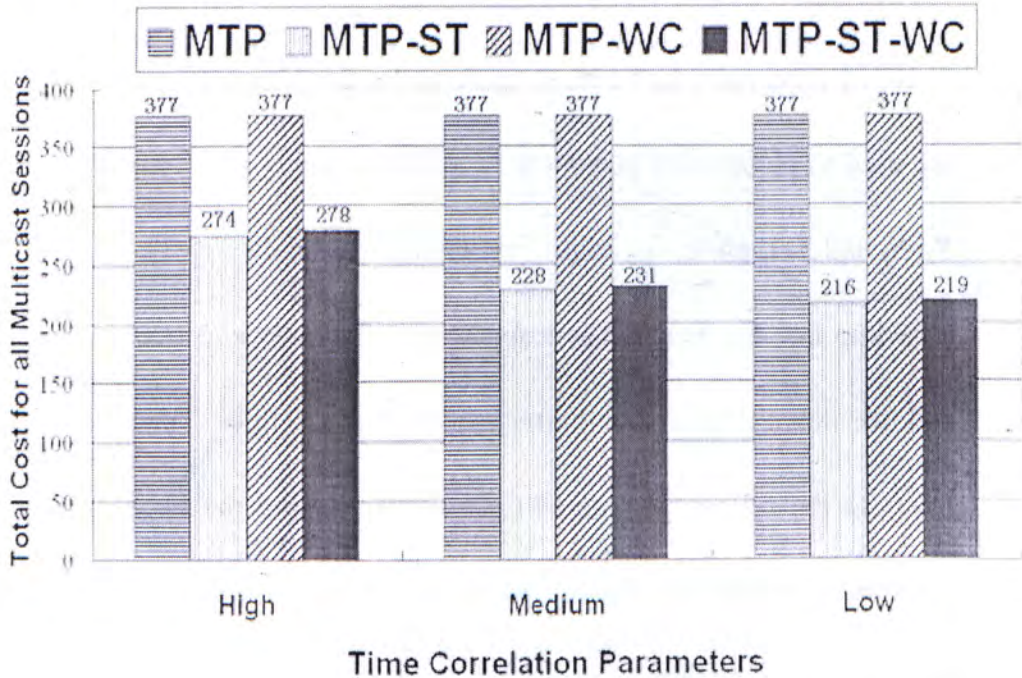


Fig. 2. 3: Costs of establishing all multicast trees under different schemes and different time correlation parameters, in Example 1



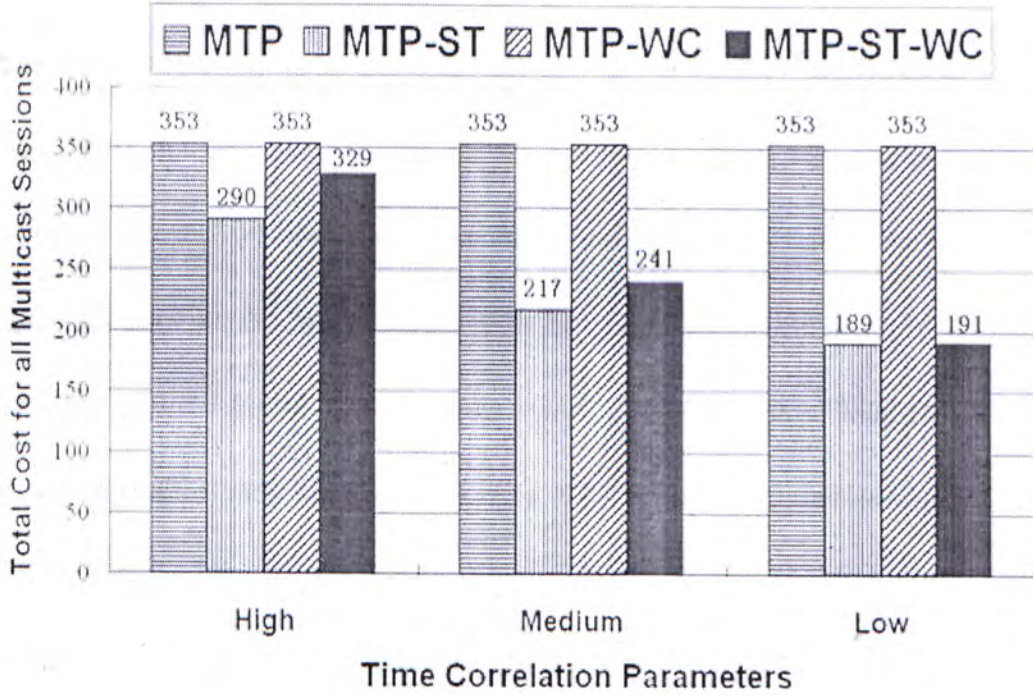


Fig. 2.4: Costs of establishing all multicast trees under different schemes and different time correlation parameters, in Example 2.

time correlations) in the above examples are chosen randomly for illustration purpose. Similar results can be derived if other traffic patterns are adopted. The ILPs are solved by CPLEX.

Fig. 2.3 and Fig. 2.4 show the costs of establishing all trees by different schemes for Example 1 and Example 2, respectively. MTP and MTP-WC refer to the previously proposed Multicast Tree Protection [2] considering no time information without and with wavelength continuity constraints, respectively. MTP-ST and MTP-ST-WC refer to our proposed Multicast Tree Protection with Scheduled Traffic formulations without and with wavelength continuity constraints, respectively. From both Fig. 2.3 and Fig. 2.4, it is observed that the lower the time correlation, the more improvement

in our proposed MTP-ST and MTP-ST-WC formulations. In Example 1, both the performance improvements of MTP-ST and MTP-ST-WC over their respective counterparts (MTP and MTP-WC) are about 27%, 39% and 42% under “High”, “Medium” and “Low” time correlations, respectively. In Example 2, the performance improvements of MTP-ST over STP are about 18%, 39% and 46% under “High”, “Medium” and “Low” time correlations, respectively; the performance improvements of MTP-ST-WC over MTP-WC are about 7%, 32% and 46% under “High”, “Medium” and “Low” time correlations, respectively. In both Example 1 and 2, the costs of MTP and MTP-WC are independent of the time correlation parameters, since no time information is considered by MTP and MTP-WC. With the additional wavelength continuity constraints, the costs of MTP-WC and

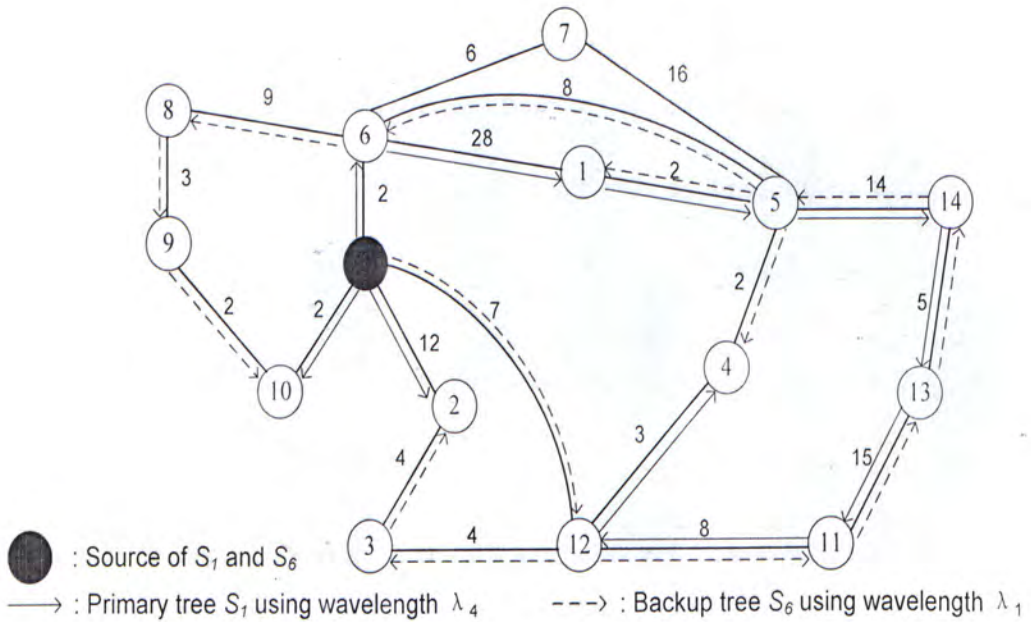


Fig. 2.5: Example 1: the established multicast primary tree  $S_1$  (blue solid arrowed lines) and its respective backup tree  $S_6$  (blue dashed arrowed lines).



MTP-ST-WC are no smaller than the costs of MTP and MTP-ST, respectively, if the same time correlation is applied. It is worthy to note that, in Example 2, some sub-optimal solutions are recorded if the optimal solution can not be obtained within certain time limits. In Example 1, Fig. 2.5 – Fig. 2.7 show the optimal RWA for all eight trees (one or two primary multicast sessions in each figure) by MTP-ST-WC under “Low” time correlation. We observe that only two wavelengths ( $\lambda_1$  and  $\lambda_4$ ) are needed to establish all the multicast trees. From Fig. 2.5, we can see that the primary tree  $S_I$  and its backup tree  $S_6$  can share a link only in opposite directions (for example, the link between node 1 and node 5). This is because we adopt directed-link-disjoint backup tree protection in this work. In addition, we can see that different trees which do not overlap in time can share a wavelength in the same

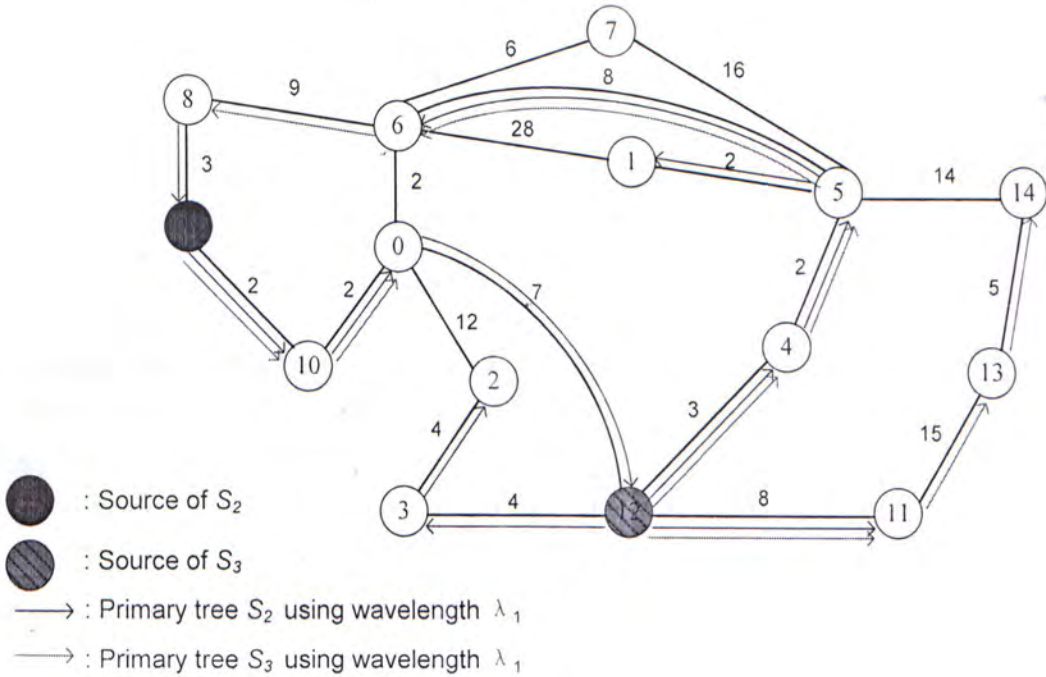


Fig. 2.6: Example 1: the established multicast primary tree  $S_2$  (blue solid arrowed lines) and primary tree  $S_3$  (red solid arrowed lines)





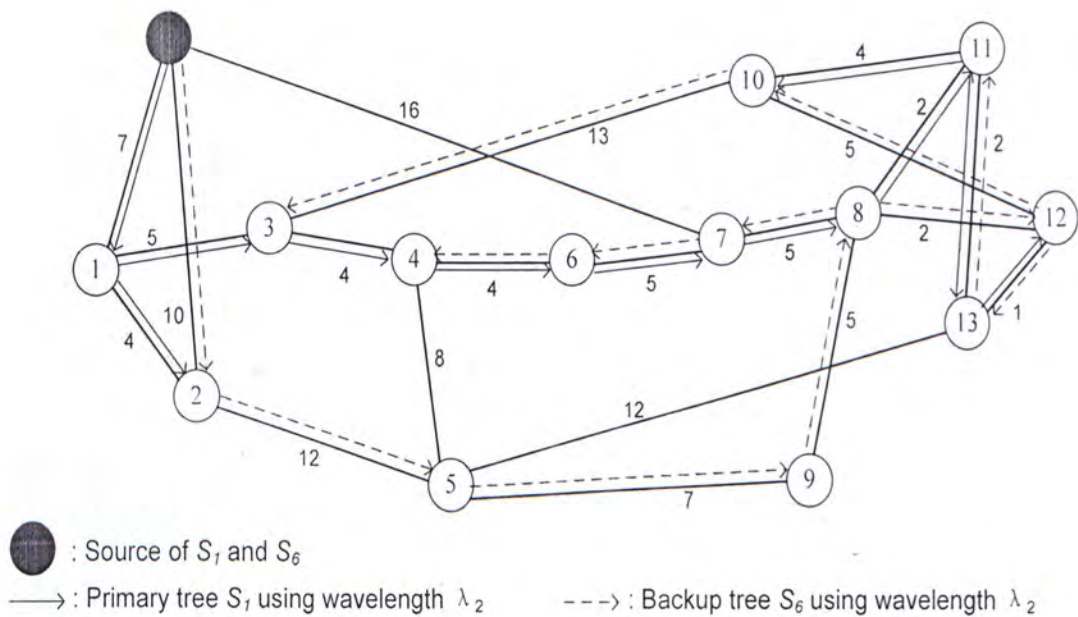


Fig. 2.8: Example 2: the established multicast primary tree  $S_1$  (blue solid arrowed lines) and its respective backup tree  $S_6$  (blue dashed arrowed lines).

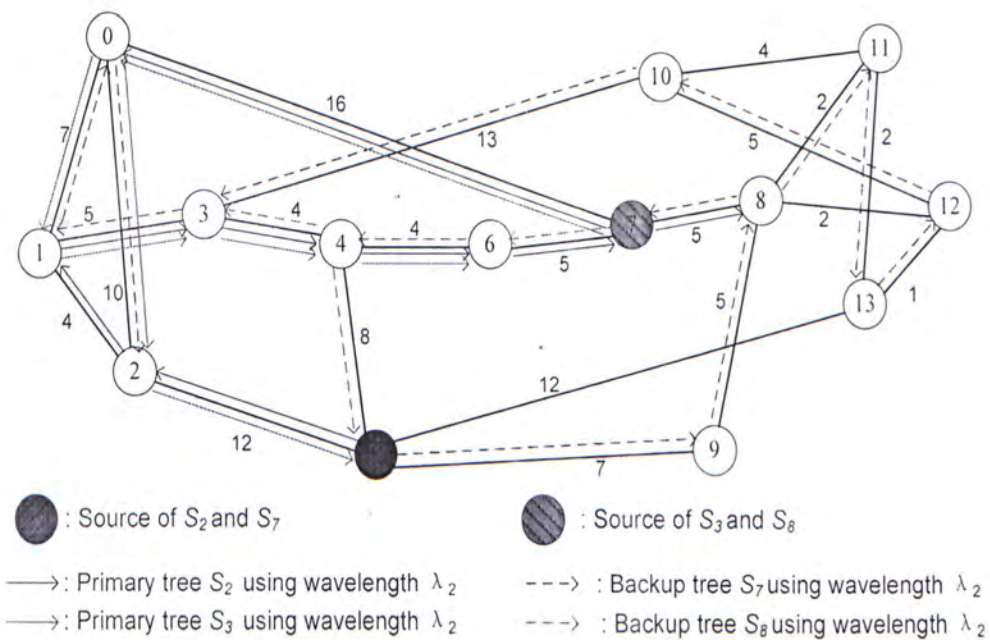


Fig. 2.9: Example 2: the established multicast primary tree  $S_2$  (blue solid arrowed lines) and its respective backup tree  $S_7$  (blue dashed arrowed lines), primary tree  $S_3$  (red solid red arrowed lines) and its respective backup tree  $S_8$  (red dashed arrowed lines)

In Example 2, similar results as Example 1 can be obtained. Fig. 2.8 - Fig. 2.10 show the optimal or sub-optimal RWA for all ten trees (one or two primary multicast sessions in each figure) by MTP-ST-WC under “Low” time correlation. We can observe that all ten multicast trees (including the backup trees) use the same wavelength  $\lambda_2$  (any other wavelength can also be chosen without changing the total costs). In Fig. 2.8, we can see that the primary tree  $S_1$  and its backup tree  $S_6$  can share a link only in opposite directions (for example, the link between node 6 and node 7). This is because we adopt directed-link-disjoint backup tree protection in this work. From Fig. 2.9, we can see that both tree  $S_2$  and  $S_3$  use the same wavelength  $\lambda_2$  on the link from node 3 to node 4, link from node 4 to node 6, etc, because the two trees do not overlap in time ( $T_{2,3} = 0$  under “low” time correlation). By jointly observing Fig. 2.9 and Fig. 2.10, tree  $S_3$  (or  $S_8$ ) do not share any wavelength in the same direction of a link with tree  $S_4$  (or  $S_9$ ) and tree  $S_5$  (or  $S_{10}$ ), even if they all use the same wavelength  $\lambda_2$ . This is because “low” time correlation is applied where  $T_{3(8),4(9)} = T_{3(8),5(10)} = 1$ .



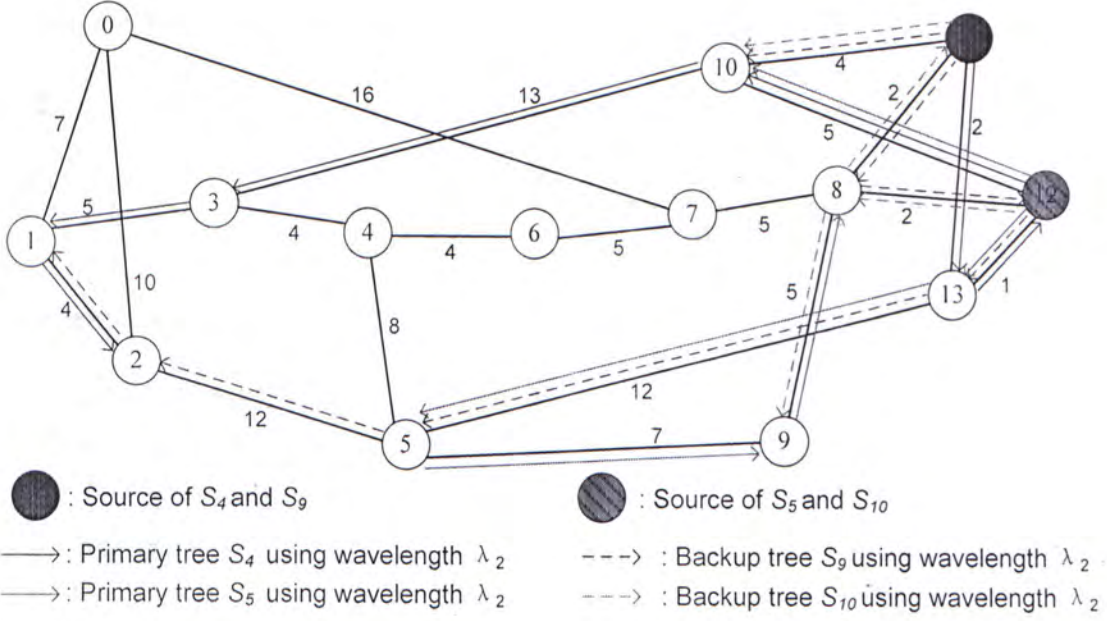


Figure 2.10: Example 2: the established multicast primary tree  $S_4$  (blue solid arrowed lines) and its respective backup tree  $S_9$  (dashed arrowed lines), primary tree  $S_5$  (red solid red arrowed lines) and its respective backup tree  $S_{10}$  (red dashed arrowed lines)

## 2.4 Two-Step Optimization under SSTM

To deal with the RWA of multicast sessions under SSTM, we adopt a two-step optimization approach similar to that in [10]. We observe from previous section that the lower the time-overlap degree, the more cost savings. SSTM gives operators more flexibility to reduce the time-overlap degree. In the first step, each multicast session is optimally scheduled within its specified larger time window in order to minimize the time-overlap degree. In the second step, the problem is reduced to the FSTM problem and can be solved by our proposed ILPs in the previous Section. We divide the problem into two parts because the single MILP to derive the optimal results consumes much more time. In the following, a Mixed Integer Linear Programming (MILP) which can be solved immediately for reasonably large network

(e.g. NSFNET) is formulated to optimally slide each multicast session within is specified larger time window in the first step:

The inputs of the MILP formulation are listed as follows:

A set of  $k$  primary multicast sessions (trees).  $L_i$  and  $P_i$  have the same meanings as in Section 2.2.  $(t_{is}, t_{ie})$  is a larger time window during which  $S_i$  must be provisioned and  $\tau_i$  is the holding time of  $S_i$ .  $M$  is the time duration from earliest window start time and the latest window end time of the  $k$  windows.

The variables for the MILP are defined as follows:

- ✓ Boolean variable  $T_{i,j}$  indicates whether tree  $S_i$  and tree  $S_j$  overlap in time (=1) or not (=0). In MILP formulation,  $T_{i,j}$  is variable. After being solved in MILP, it is used as inputs to the ILP in the second step.
- ✓  $ST_i$  is the actual start time of multicast session  $S_i$ .
- ✓ Boolean variable  $Y_{i,j}$  indicates that whether  $S_i$  ends after  $S_j$  starts, i.e.  $ST_i + \tau_i - ST_j > 0$ . Note that  $Y_{i,j}$  and  $Y_{j,i}$  are not symmetrical.

The objective of the MILP is:

$$\text{Minimize} \quad \sum_{1 \leq i < j \leq k} [L_i(P_i + 1)L_j(P_j + 1)]T_{i,j} \quad (2-19)$$

Subject to:

$$\forall 1 \leq i \leq k, ST_i \geq t_{is} \quad (2-20)$$

$$\forall 1 \leq i \leq k, ST_i + \tau_i \leq t_{ie} \quad (2-21)$$

$$\forall 1 \leq i \leq k, 1 \leq j \leq k, i \neq j, ST_i + \tau_i - ST_j \leq MY_{i,j} \quad (2-22)$$

$$\forall 1 \leq i < j \leq k, Y_{i,j} + Y_{j,i} - T_{i,j} \leq 1 \quad (2-23)$$

$$\forall 1 \leq i < j \leq k, Y_{i,j} - T_{i,j} \geq 0 \quad (2-24)$$

$$\forall 1 \leq i < j \leq k, Y_{j,i} - T_{i,j} \geq 0 \quad (2-25)$$

Explanation of MILP:

- ✓ The objective (2-19) is to minimize the total time-overlap degree of multicast sessions. The weight of each pair of time overlap is proportional to the product of the expected bandwidth consumption.
- ✓ Equation (2-20) and (2-21) ensures that each multicast session is scheduled within its specified larger time window.
- ✓ Equation (2-22) defines the meaning of  $Y_{i,j}$ .
- ✓ Equation (2-23) ensures that if both  $Y_{i,j}$  and  $Y_{j,i}$  are equal to 1, session  $S_i$  and  $S_j$  must overlap with each other in time.
- ✓ Equation (2-24) and (2-25) ensure that if session  $S_i$  and  $S_j$  overlap in time, each of them ends after the other starts.

For example, we assume there are five primary multicast sessions which are the same as those in Example 1 in the previous section. The larger time windows for the five multicast sessions are (00:00, 03:00), (02:00, 04:30), (05:00, 06:00), (08:00, 10:00), (08:00, 10:00), respectively. The holding time for the five multicast sessions are  $\tau_1 = 2.5$  (h),  $\tau_2 = 1.2$  (h),  $\tau_3 = 1$ (h),  $\tau_4 = 1$ (h),  $\tau_5 = 1$  (h), respectively. We use CPLEX to



solve the MILP formulated before. The solutions of this example are  $T_{i,j} = 0$  ( $1 \leq i < j \leq 5$ ). And the actual start times of the five multicast sessions are  $ST_1 = 00:00$ ,  $ST_2 = 03:00$ ,  $ST_3 = 05:00$ ,  $ST_4 = 08:00$ ,  $ST_5 = 09:00$ , respectively. After the MILP has been solved in the first step, the solutions ( $T_{i,j}$ ) can be inputted into the ILP formulated in section 2 in the second step. So after the two-step optimization, the RWA problem of survivable multicast sessions under SSTM has been solved.

## 2.5 Summary

We have formulated and numerically investigated the multicast tree protection with scheduled traffic. Firstly, we have proposed an ILP which can minimize the total costs of establishing all multicast sessions under FSTM. The results show that the network resources can be jointly optimized both in space and time to provision survivable multicast sessions at much lower costs compared to the previous schemes which are unaware of the traffic time information. Secondly, we have adopted a two-step optimization approach to deal with the survivable multicast provisioning problem under SSTM. Although ILP can find the optimal solutions to the multicast protection problem with scheduled traffic, it would require large amount of running time in the scenario where a large network or heavy traffic load is applied. As a result, our future works will focus on investigating heuristics on finding the optimal RWA of survivable multicast sessions with scheduled traffic.

# **Chapter 3 Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks**

## **3.1 Introduction**

The energy consumption of the backbone network is rapidly growing with the traffic and thus the concept of “Green Networking” has recently aroused much attention from the research community. Therefore it is highly desirable to minimize the energy consumption in network planning and resource optimization.

Traffic grooming problem in optical wavelength routing network has been extensively studied with the aims to minimize the number of optical-electronic-optical conversions (OEOs), or maximize the total number of users served in the optical networks. Thus, the network bandwidth utilization can be optimized. In [13], a mathematical formulation of traffic grooming and several heuristics were proposed in order to improve the network throughput. In [14], a novel generic graph model was proposed to achieve various traffic grooming policies by just modifying the weights of the edges in the graph model. Both [13] and [14] dealt with static traffic grooming problem in which all connection requests were known in advance. In [15], the novel generic graph model in [14] was applied to a dynamic traffic grooming problem in which connection requests arrived at the network randomly. In [16], a layered Grooming Graph was proposed to investigate the survivable traffic grooming algorithms. In [17], the holding time information of connections was exploited to improve the traffic grooming performance in terms of



blocking probability. In [18], the traffic grooming problem was studied under a sliding scheduled traffic model in which the holding duration of connections could slide in a larger time window.

Since traffic grooming requires electrical multiplexing and OEO conversion which induce much energy consumption, recently, there is growing interest in achieving energy efficient traffic grooming. In [19], both MILP and heuristics were reported to solve the energy-minimized static traffic grooming problem for IP over WDM Networks. In [20], two different models of power consumption of optical networks were proposed: flow based formulation and interface based formulation. The work in [21] adopted the interface based formulation and formulated an Integer Linear Programming (ILP) for the traffic grooming problem with the objective of minimizing the power consumption. In [22] and [23], a more detailed energy consumption model considering the modular structure of optical network nodes was presented and a similar layered graph model to [14] was adopted to solve the dynamic traffic grooming problem.

As far as we know, existing works on energy-efficient traffic grooming do not consider a very important factor in energy saving – time, as energy consumption is the product of both power and time. Hence, minimizing the power consumption may not necessarily minimize the energy consumption. In this paper, we study both static and dynamic traffic grooming problems with an additional consideration of time information.



## 3.2 Energy consumption model

In this paper, we adopt the interface based formulation in [21] as the power consumption model. In this model, it is assumed that the main power consumption components in optical network are the ports of DXC (Digital Cross Connect) and OEO conversions. Compared to electronic domain, optical domain components consume much less power. So the power consumption of the whole network is calculated as the sum of the power consumption of individual light-paths. The power consumption of a light-path  $P_{lightpath}$  is assumed to have a linear dependence with the amount of traffic and is represented as:

$$P_{lightpath} = P_0 + p \times b_l \quad (3-1)$$

where  $P_0$  is the fixed power consumption once the components of a light-path are turned on, even if the light-path carries no traffic.  $p$  is the coefficient which denotes the power consumption per additional unit traffic.  $b_l$  denotes the amount of traffic carried on the light-path. It is also assumed that the inactive components can be shut down when there is no traffic. As far as we know, there is still lack of accurate power consumption model for optical network components. Although our work adopts interface based formulation, for simplicity, our following formulation and algorithms are applicable to other power consumption models by just modifying the objective function in the static traffic grooming and modifying the Grooming Graph in the dynamic case.

## 3.3 Static Traffic Grooming with Time awareness

### 3.3.1 Scheduled Traffic Model for Traffic Grooming

In static traffic grooming with holding time awareness, all connection requests with their setup and tear-down times are known in advance. This is similar to the Scheduled Traffic Model in previous Chapter. Each connection request is represented by  $r(s, d, b, t_s, t_e)$ , where  $s$  and  $d$  denote the source and destination node, respectively;  $b$  denotes the bandwidth requested, which is the amount of traffic in units of the minimal granularity (e.g., OC-1);  $t_s$  and  $t_e$  are the requested setup and tear-down times, respectively.

### 3.3.2 ILP Formulation

The network topology  $G = (V, E)$  is given as an undirected graph.  $V$  is the set of network nodes capable of traffic grooming.  $E$  is the set of undirected fiber links. It is assumed that each fiber can support  $W$  wavelengths and the capacity of each wavelength is in multiples of the minimal granularity (e.g., OC-1), represented by  $C$ . The set of all connection requests is denoted by  $R$ . The connection requests and the established light-paths are both bidirectional.  $b_r$  denotes the bandwidth requested by connection request  $r$ . In static traffic grooming, we assume that the network capacity of the network is sufficient to accommodate all connection requests. The objective of our ILP formulation is to minimize the total energy consumption of establishing all the connection requests.

In the formulation, the setup and tear-down times of all connection requests divide the continuous time period into time slots, whose duration may not be equal to each other. For example, suppose there are two connection requests:  $r_1$  with setup time 00:00 and tear-down time 04:00, and  $r_2$  with setup time 01:00 and tear-down time 02:00. Then the time is divided into three time slots  $T_1(00:00-01:00)$ ,  $T_2(01:00-02:00)$ ,  $T_3(02:00-04:00)$ . Time slot  $a$  is denoted by  $T_a$ ,  $a \in \{1, 2, 3, \dots\}$ . And  $|T_a|$  denotes the duration of the time slot. The set of all time slots is denoted by  $T$ .

The variables of the ILP are listed as follows:

$V_{ij}^{T_a}$  : number of light-paths between node  $i$  and node  $j$ , in time slot  $T_a$ .

$V_{ij}^{w, T_a}$  : number of light-paths between node  $i$  and node  $j$  using wavelength  $w$ , in time slot  $T_a$ .

$P_{mn, T_a}^{ij, w}$  : number of light-paths between node  $i$  and node  $j$  routed through fiber link  $(m, n)$  using wavelength  $w$ , in time slot  $T_a$ .

$\lambda_{ij}^{r, T_a}$  : boolean variable which indicates whether connection request  $r$  is routed through a light-path between node  $i$  and node  $j$ , in time slot  $T_a$ .

$X_{k, T_a}^{ij, w}$  : number of light-paths between node  $i$  and node  $j$  routed through node  $k$  ( $k \neq i, j$ ) using wavelength  $w$ , in time slot  $T_a$ .

$Y_k^{r, T_a}$  : boolean variable which indicates whether connection request  $r$  is electronically routed through the intermediate node  $k$  ( $k \neq$  the source and destination



of  $r$ ), in time slot  $T_a$ .

The objective of the ILP is to minimize the total energy consumption which comprises a traffic independent part and a traffic dependent part:

$$\sum_{T_a \in T} \{ P_0 \sum_{ij} V_{ij}^{T_a} + p \sum_{ij} \sum_{r \in R} b_r \times \lambda_{ij}^{r, T_a} \} \times |T_a| \quad (3-2)$$

Subject to:

Virtual topology constraint:

$$\sum_w V_{ij}^{w, T_a} = V_{ij}^{T_a}, \forall i, j, T_a \quad (3-3)$$

Equation (3-3) ensures that the total number of light-paths between node  $i$  and node  $j$  is the sum of the number of light-paths on different wavelengths between the two nodes.

Wavelength routing constraints:

$$\sum_n P_{in, T_a}^{ij, w} = V_{ij}^{w, T_a}, \forall i, j, w, T_a \quad (3-4)$$

$$\sum_m P_{mj, T_a}^{ij, w} = V_{ij}^{w, T_a}, \forall i, j, w, T_a \quad (3-5)$$

Equation (3-4) and (3-5) are the flow conservation equations of the two ends of light-paths.

$$X_{k, T_a}^{ij, w} \leq V_{ij}^{w, T_a}, \forall i, j, w, T_a, k \neq i, j \quad (3-6)$$

Equation (3-6) ensures that the number of light-paths going through an intermediate

node using a particular wavelength is equal to or less than the total number of light-paths between the two ends using that wavelength.

$$\sum_m P_{mk, T_a}^{ij, w} = 2 \times X_{k, T_a}^{ij, w}, \forall i, j, w, T_a, k \neq i, j \quad (3-7)$$

Equation (3-7) ensures that if a light-path goes through an intermediate node, it would also go through two neighboring fiber links of the intermediate node.

Equation (3-6) and (3-7) are flow conservation equations of intermediate nodes of light-paths.

$$\sum_{ij} P_{mn, T_a}^{ij, w} \leq 1, \forall m, n, w, T_a \quad (3-8)$$

Equation (3-8) ensures that each wavelength in a fiber link can only be employed once.

Connection request constraints:

$$\sum_j \lambda_{sj}^{r, T_a} = 1, \quad \forall r, \forall T_a \quad \text{in the duration of } r. \quad (3-9)$$

$$\sum_i \lambda_{id}^{r, T_a} = 1, \quad \forall r, \forall T_a \quad \text{in the duration of } r. \quad (3-10)$$

Equation (3-9) and (3-10) are the flow conservation equations of the two ends of connection requests.

$$\sum_{r \in R} \lambda_{ij}^{r, T_a} \times b_r \leq V_{ij}^{T_a} \times C, \forall i, j, T_a \quad (3-11)$$

Equation (3-11) ensures that the total bandwidth of all connection requests between two nodes is limited by the capacity of light-paths between them.

$$\sum_i \lambda_{ik}^{r,T_a} = 2 \times Y_k^{r,T_a}, \forall r, T_a, \forall k \neq \text{the source or destination of } r. \quad (3-12)$$

Equation (3-12) ensures that if a connection request goes through an intermediate node, it would also go through two neighboring virtual links of the intermediate node, which is a flow conservation equation of connection requests.

$$\lambda_{ij}^{r,T_a} = \lambda_{ij}^{r,T_b}, \text{ if } T_a \text{ and } T_b \text{ are both in the duration of } r. \quad (3-13)$$

Equation (3-13) ensures that each connection request would keep its route within its holding duration.

### 3.3.3 Illustrative Numerical Example

It is well known that traffic grooming problem is NP-complete. So we employ the small 6-node network shown in Fig. 3.1 to illustrate our formulation. Each link carries 2 wavelengths and each wavelength's capacity  $C$  is OC-48. There are totally four connection requests:  $r_1(0, 2, \text{OC-12}, 00:00, 04:00)$ ,  $r_2(2, 4, \text{OC-12}, 00:00, 03:00)$ ,

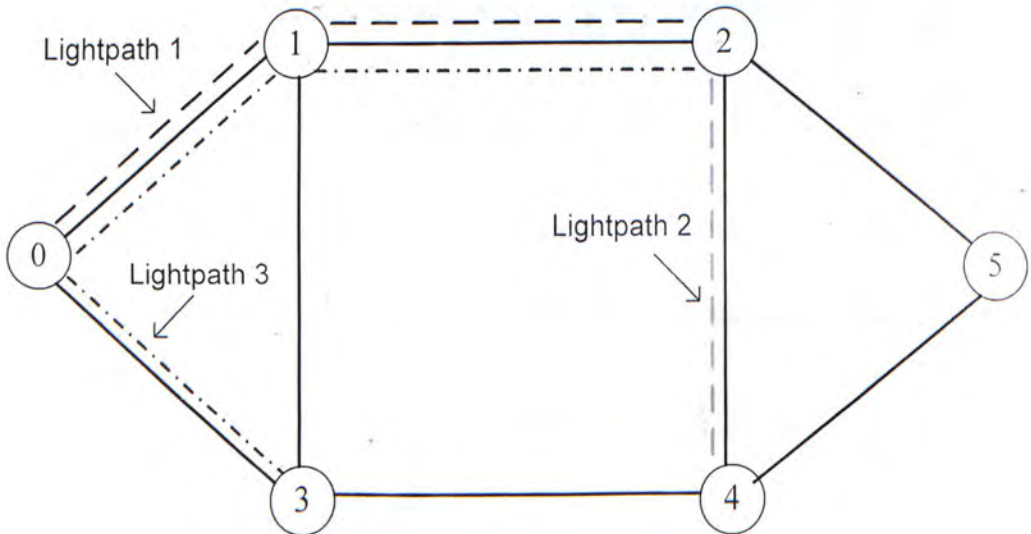


Fig. 3.1: Established light-paths in the illustrative numerical example.



$r_3(0, 4, \text{OC-3}, 00:00, 02:00)$ ,  $r_4(2, 3, \text{OC-3}, 02:00, 04:00)$ . We normalize  $P_{\max} = P_0 + p \times C = 1$ . Take  $P_0 = 0.25$ . So  $p = 0.75/48 = 0.015625$ .

According to the setup and tear-down times of the four connection requests, there are totally 3 time slots:  $T_1(00:00-02:00)$ ,  $T_2(02:00-03:00)$ ,  $T_3(03:00-04:00)$ . After solving the ILP, Fig. 3.1 shows the three light-paths being established as well as their holding periods: Light-path 1 between node 0 and node 2 (00:00-04:00); Light-path 2 between node 2 and node 4 (00:00-03:00); and Light-path 3 between node 2 and node 3 (02:00-04:00). And  $r_1$  goes through Light-path 1,  $r_2$  goes through Light-path 2,  $r_3$  goes through both Light-paths 1 and 2,  $r_4$  goes through Light-path 3, all in their respective requested holding times. In this example, the total energy consumption of establishing all connection requests is: 3.84375.

### 3.4 Dynamic Traffic Grooming with Time Awareness

In dynamic traffic grooming, connections arrive one at a time randomly and hold for the requested durations. The connection request is then represented by  $r(s, d, b, h)$ , where  $h$  denotes the requested holding time of the request. When a connection request arrives, the network operator should determine the route of this connection immediately. In this dynamic scenario, ILP is not feasible because of the real time requirement. Different kinds of heuristics have been proposed to solve the dynamic traffic grooming problem. The Novel Generic Graph Model proposed in [14] and the Grooming Graph Model proposed in [16] have similar layered structure and can achieve various objectives using different grooming policies by just adjusting the

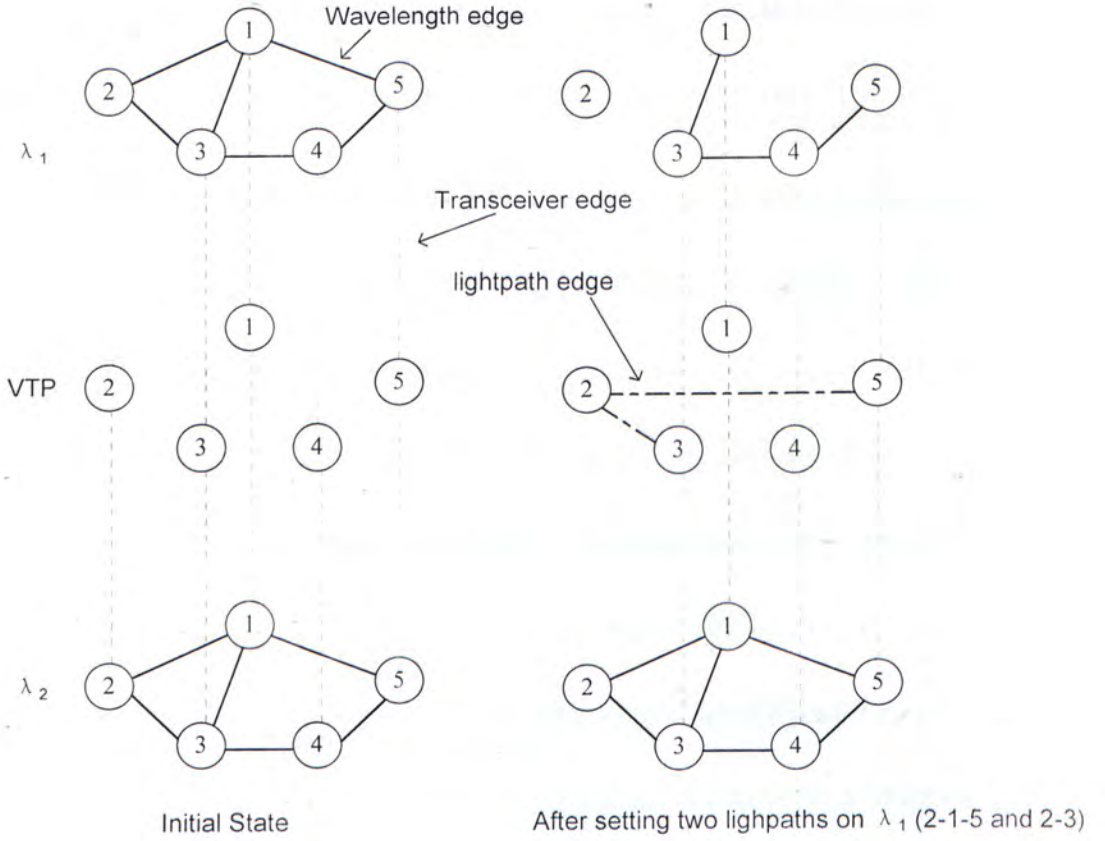


Fig. 3.2: Grooming Graph

weights of the edges. In this paper, we adopt the Grooming Graph Model in [16] which is an undirected layered graph for simplicity. We employ this Grooming Graph to implement our newly proposed TATG algorithm, as well as the previously reported grooming policies such as MinLP, MinHops [15][21].

The Grooming Graph has totally  $W+1$  planes, where  $W$  is the number of different wavelengths the network can support. Each wavelength is corresponding to a Wavelength Plane (WP) ( $\lambda_i$ ,  $1 \leq i \leq W$ ). And there is an additional plane called Virtual Topology Plane (VTP). The nodes in each plane correspond to the nodes in the physical topology. Fig. 3.2 shows the Grooming Graph for a 5-node network supporting 2 wavelengths, as an example.

There are three kinds of edges in the Grooming Graph:

**Light-path edge:** there is a light-path edge between two nodes in the VTP if there is a light-path between the two corresponding physical nodes.

**Wavelength edge:** there is a wavelength edge between two nodes in the WP  $\lambda_i$  if there is fiber link between the two nodes and wavelength  $\lambda_i$  is free in this fiber link.

**Transceiver edge:** there is transceiver edge between the corresponding nodes in VTP and a WP if there is an unused transceiver. In this paper, we assume there are always enough wavelength tunable transceivers in each physical node. So, in our model, there are always transceiver edges between the corresponding nodes in VTP and a WP.

By adjusting the weights of these three kinds of edges, we can achieve various kinds of traffic grooming policies.

### 3.4.1 Time-Aware Traffic Grooming (TATG)

In order to save energy, according to [21], there is a tradeoff between minimizing the total number of light-paths in the network and minimizing the average number of light-paths (hops) the connection requests have gone through.

Intuitively, if we can groom a new connection request onto an existing light-path with longer remaining holding time, we can reduce the number of light-paths in the network. We illustrate the intuition by the following simple example.



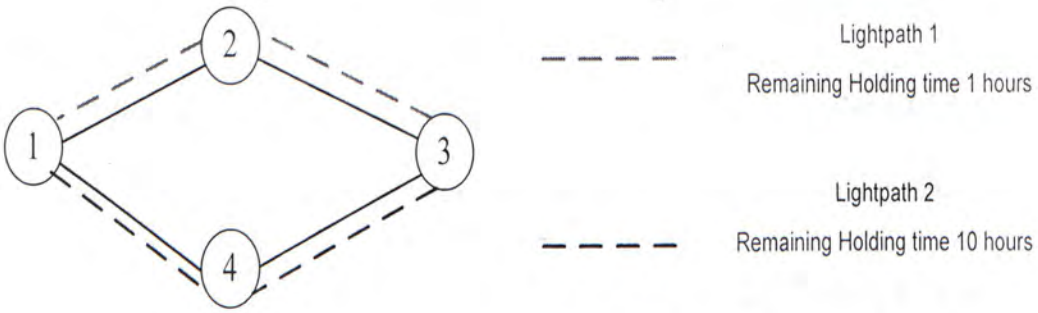


Fig. 3.3: Motivation Example

In Fig. 3.3, at certain moment, there are two existing light-paths between node 1 and node 3: Light-path 1 with remaining holding time 1 hour and Light-path 2 with remaining holding time 10 hours. At this moment, if a new connection request between node 1 and node 3 with requested holding time 4 hours arrives and both Light-path 1 and Light-path 2 have sufficient free bandwidth to accommodate the new request, intuitively, we should choose to groom the new request onto Light-path 2 rather than Light-path 1 or establish a new light-path because we can minimize the number of light-paths to 1 after Light-path 1 being released 1 hour later.

On the other hand, we do not want the connection request to go through too many light-paths (hops) in order to save energy.

The procedure of TATG is similar to the algorithms in [15] except that we adopt the following weight assignment for the three kinds of edges (3-14) to (3-16). When a connection request arrives, we can simply run the shortest-path algorithm (e.g., Dijkstra) between the two nodes in VTP corresponding to the two ends of the connection request on the Grooming Graph to derive the route of the new connection request, and then update the Grooming Graph. The selected route by the

shortest-path algorithm determines whether we should establish new light-paths and/or which existing light-paths the new connection request should be groomed onto.

So in the proposed TATG algorithm, we adopt the following weight assignments to the three kinds of edges in Grooming Graph:

$$W_{lightpath} = \begin{cases} p \times b_r \times h, h \leq H_l \\ p \times b_r \times h + P_0(h - H_l), h > H_l \end{cases} \quad (3-14)$$

$$W_{transceiver} = (P_0 + p \times b_r)h / 2 \quad (3-15)$$

$$W_{wavelength} = \delta \quad (3-16)$$

$H_l$  is the remaining holding time of the corresponding light-path;  $b_r$  is the requested bandwidth of the request;  $h$ ,  $P_0$ ,  $p$  have the same meanings as described before;  $\delta$  is a very small real number (e.g., 0.00001). This weight assignment scheme assigns the actual newly induced energy consumption by each edge as its weight if the edge is chosen by the shortest-path algorithm. For example, in (3-14), if  $h \leq H_l$ , the newly induced energy consumption of a light-path is only the traffic dependent part. If  $h > H_l$ , the light-path has to be sustained for an additional time duration of  $h - H_l$ , which would cause traffic independent energy consumption. In (3-15), a new light-path would be established if two corresponding transceiver edges are chosen. So TATG minimize the newly increased energy consumption induced by each new connection request.

In order to compare the energy efficiency of different policies, MinLP [15] and MinHops (referred as MinTHV in [15] and minT in [21]) are also implemented by just adjusting the weights of the three kinds of edges:

- ✓ **MinLP:** This policy tries to minimize the number of newly established light-paths to carry the arriving connection request. To implement this policy, we configure the weight of transceiver edge much larger than that of light-path edge. And the weight of light-path edge is much larger than that of wavelength edge.
- ✓ **MinHops:** This policy tries to minimize the number of hops (light-paths or virtual links) the connection request goes through. To implement this policy, we configure the weight of transceiver edge just half of that of the light-path edge. And both of their weights are much larger than that of the wavelength edge.

### 3.5 Simulation Results of Dynamic Traffic Grooming

In this section, we compare the performance of different traffic grooming policies in terms of energy consumption, average number of hops and blocking probability under various traffic loads. All the nodes are capable of traffic grooming but have no wavelength conversion capability. Each fiber link is bidirectional with 16 wavelengths and the capacity of each wavelength is OC-192. The traffic arrival process is Poisson process and the holding time is exponentially distributed with its mean value set to 1. All the connection requests are bidirectional and uniformly distributed among all the node pairs. There are four types of connection requests:



OC-3, OC-12, OC-48 and OC-192, and the proportion of the number of these connection requests are 8:4:2:1. A connection request cannot be divided into several lower speed connections and routed separately. Re-routing of existing connections is not allowed. Each data point in the following figures is averaged over a total number of 50000 connection requests. In the energy consumption model, the maximum power consumption of a single light-path is normalized to 1 and  $P_0$  is firstly set to 0.25 which is the same as in [10]. Other configuration of  $P_0$  ( $0 \leq P_0 \leq 1$ ) would lead to similar conclusions as shown in later simulation results in 3.5.4.

### 3.5.1 24-node USNET:

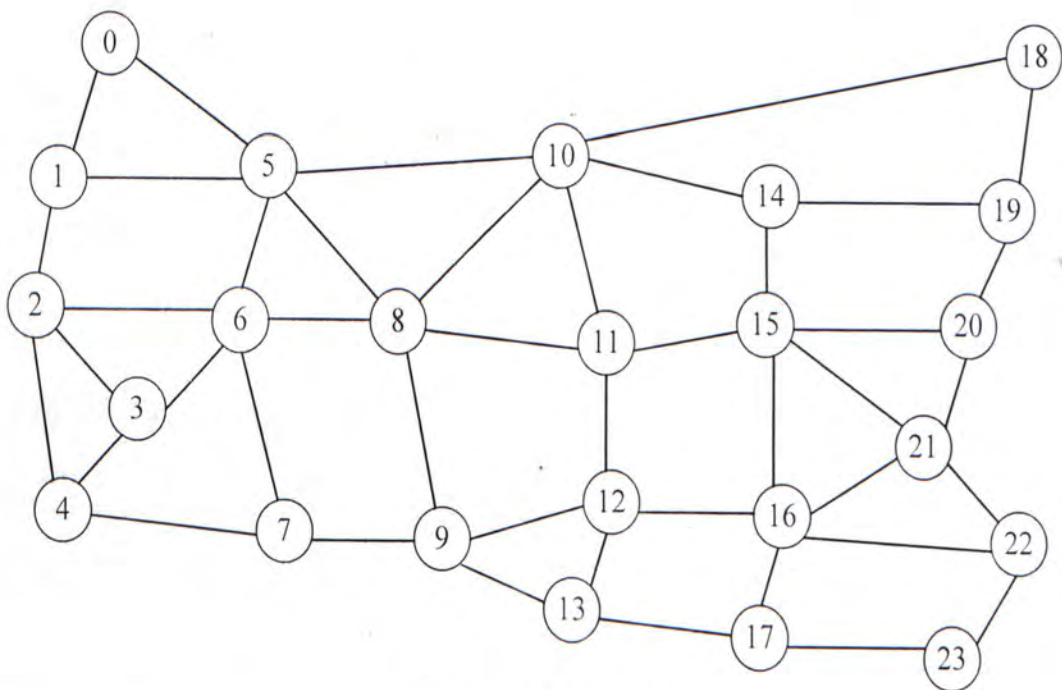


Fig. 3.4.: 24-node USNET

The 24-node USNET shown in Fig. 3.4 is employed for the first set of experiments.

Fig. 3.5 shows the energy consumption of the three kinds of traffic grooming policies

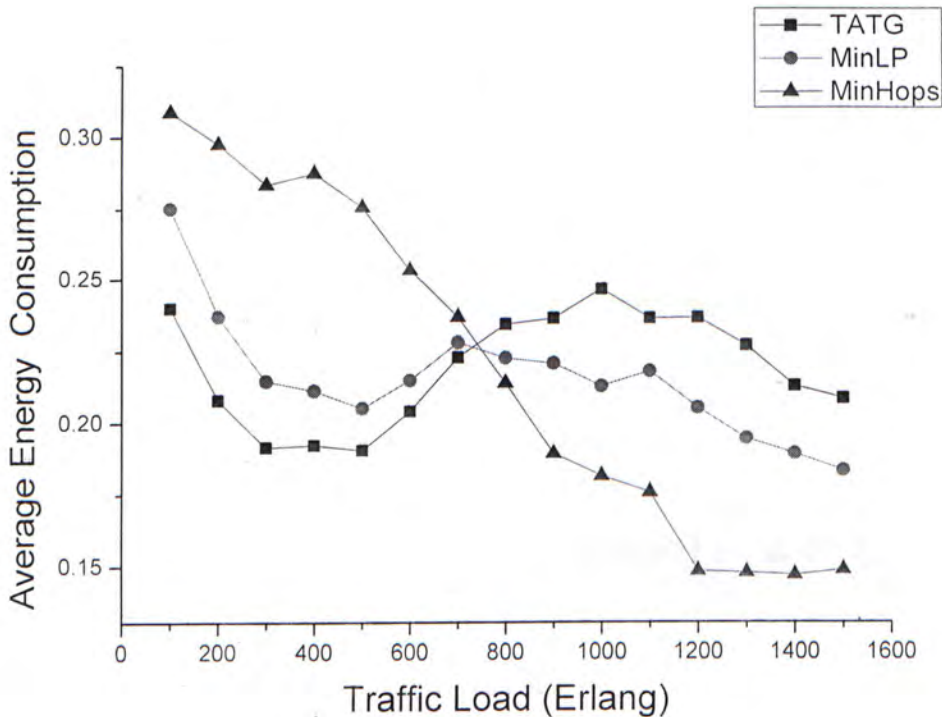


Fig. 3.5: Average energy consumption per connection

under various traffic loads. We observe that TATG achieves the least energy consumption when traffic load is relatively low and MinHops achieves the best performance when traffic load is relatively high. This is because, when traffic load is relatively low, TATG grooms traffic together as much as possible by trying to route new connection requests through the existing light-paths with longer remaining holding time. On the contrary, MinHops tends to establish new lighpaths directly which induces unnecessary energy consumption. However, when traffic load is relatively high, this advantage of TATG diminishes because other policies also groom traffic together intensively in order to accommodate more traffic. In addition, when the traffic load is relatively high, the average number of hops plays an

important role in determining energy consumption.

Fig. 3.6 shows the average number of hops (light-paths) per connection request goes

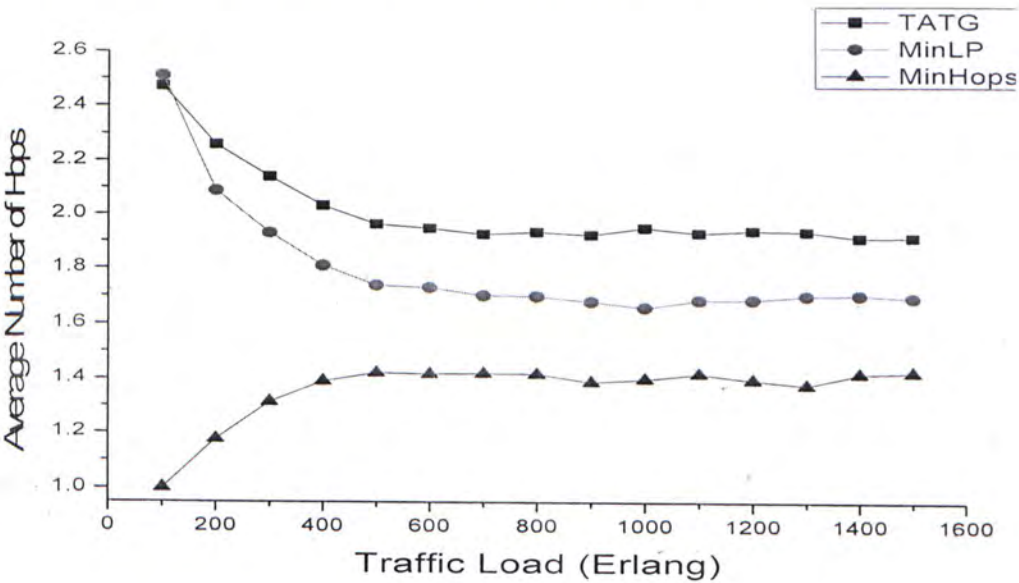


Fig. 3.6: Average number of hops (light-paths) per connection goes through

through if the three traffic grooming policies are applied. We observe that MinHops always achieves the least number of hops. When traffic load is relatively high, new light-paths are hard to establish for all the three policies. If a connection request goes through more existing light-paths (hops), the result is that more light-paths has to carry the traffic of the new connection request and hold for a longer time period, leading to more energy consumption. So this is the reason why MinHops which tries to minimize the number hops consumes the least energy when traffic load is relatively high. In our configuration of MinLP, the weight of light-path edge is much larger than that of wavelength edge, so MinLP also has an effect to minimize the number of hops, provided that the number of newly established light-paths is minimized first.



Fig. 3.7 shows the average number of wavelength links per established light-path.

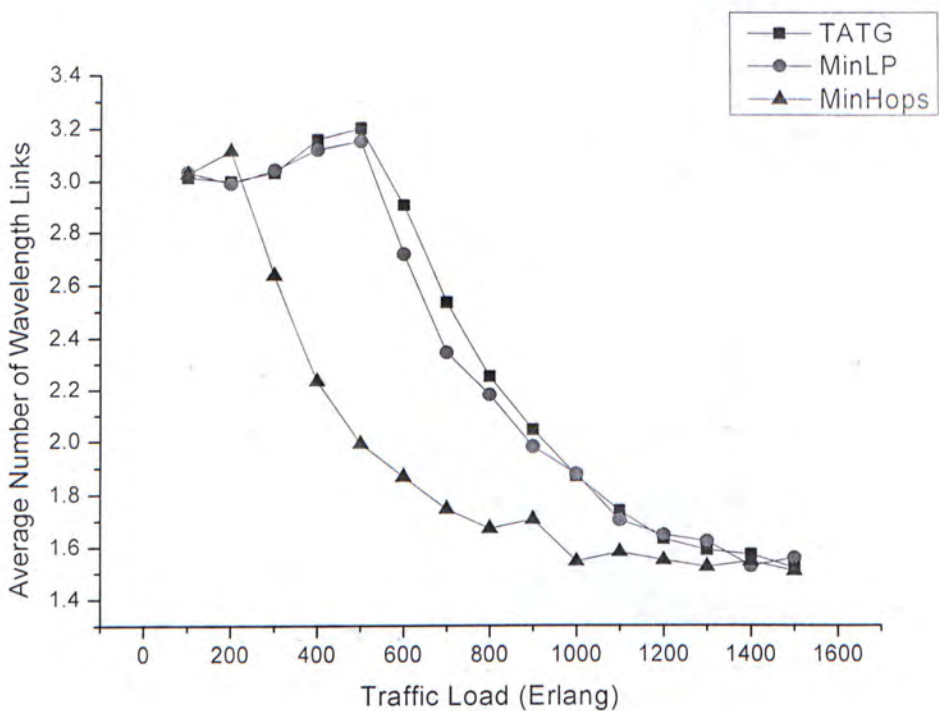


Fig. 3.7: average number of wavelength links

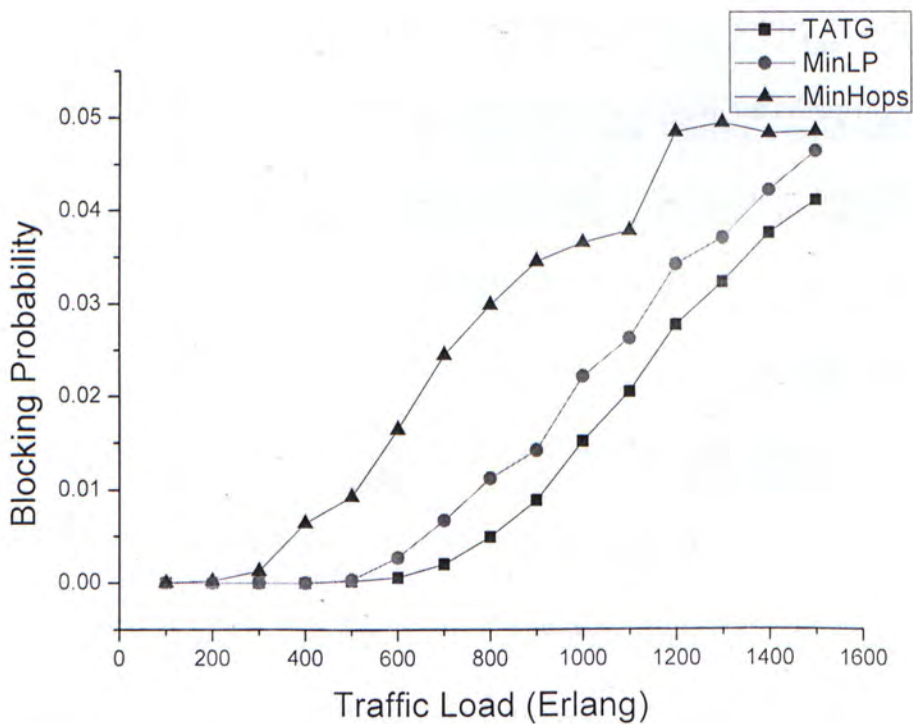


Fig. 3.8: Blocking probability

We observe that MinHops achieves the minimum. It means that the average length of the light-paths established by MinHops is the shortest among the three policies. In this topology, it can be explained by that the connections established by TATG and MinLP would rather go through several existing long light-paths than establishing a new and short light-path. Combined with the results shown in Fig. 3.6 that MinHops always achieves the minimum number of Hops (light-paths), it can be inferred that MinHops is the best choice for network operators if most traffic requires very low packet delay.

Fig. 3.8 shows the blocking probabilities of the three kinds of traffic grooming policies. We observe that TATG achieves the lowest blocking probabilities and MinHops has the highest blocking probabilities. When traffic load is relatively high, the three policies would achieve similar blocking probabilities.

The simulation results provide implications to choose the most energy-efficient grooming policies under various traffic loads. We can adopt an adaptive scheme in which TATG is employed when traffic load is relatively low and MinHops is employed when traffic load is relatively high. The exact threshold of traffic load can be determined according to network topology and traffic characteristics, as in [15]. In this example, the threshold is about 700 Erlang.

### **3.5.2 15-node Pacific Bell Network:**

The 15-node Pacific Bell Network is shown in Fig. 3.9 is employed for the second set of experiments.

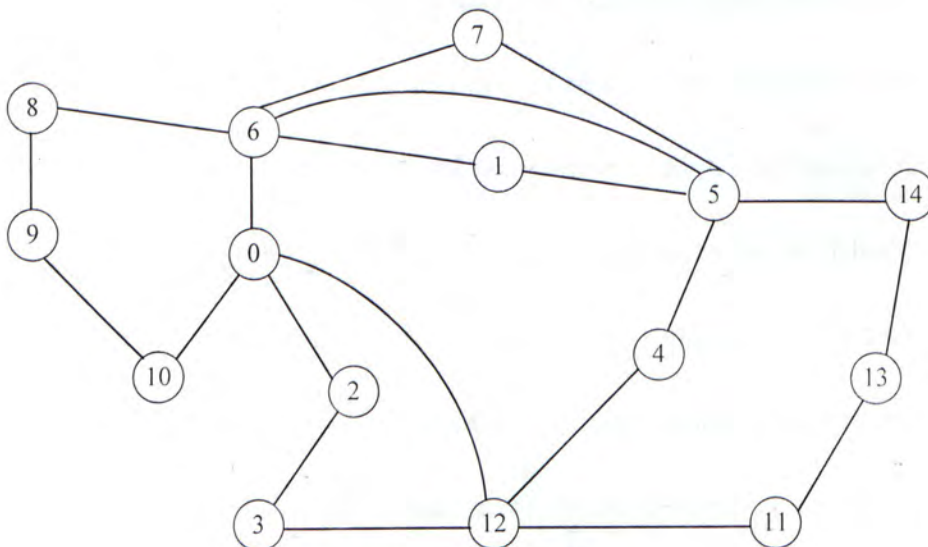


Fig. 3.9: 15-node Pacific Bell Network

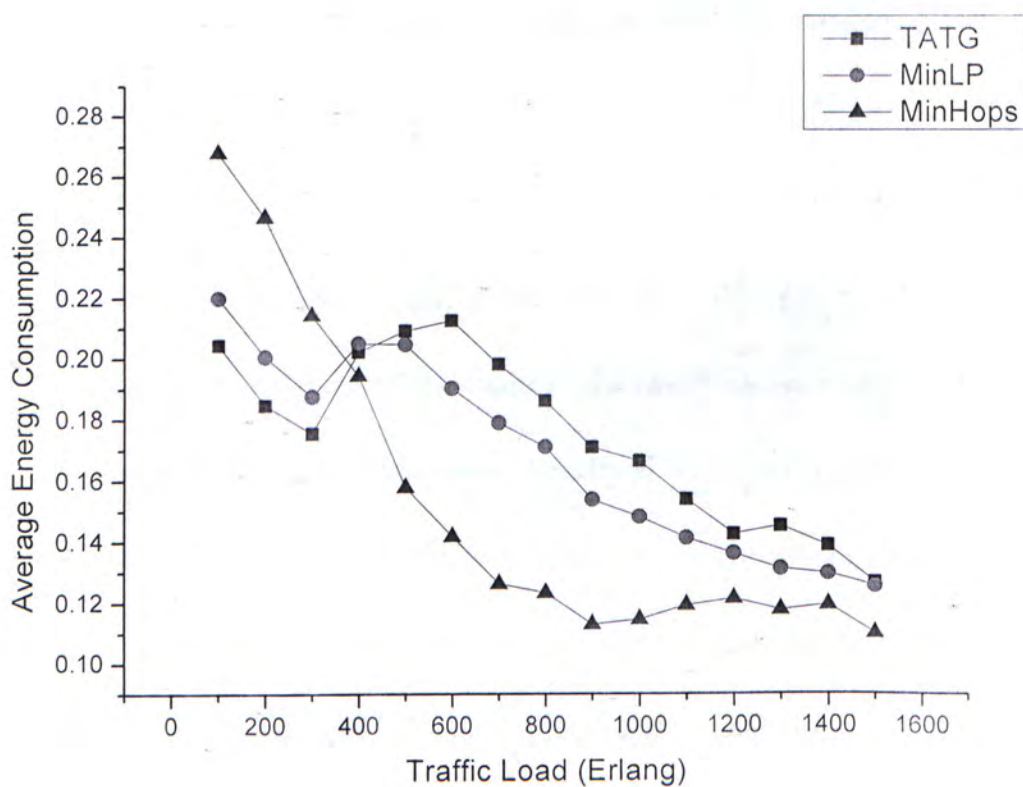


Fig. 3.10: Average energy consumption per connection



Similar to Fig 3.5, Fig. 3.10 shows the energy consumption of the three kinds of traffic grooming policies under various traffic loads. We observe that TATG achieves the least energy consumption when traffic load is relatively low and MinHops achieves the best performance when traffic load is relatively high. When traffic load is even higher, the three policies would achieve similar energy consumption performances. This is because, when traffic load is relatively low, TATG grooms traffic together as much as possible by trying to route new connection requests through the existing light-paths with longer remaining holding time. On the contrary, MinHops tends to establish new lighpaths directly which induces unnecessary energy consumption. However, when traffic load is relatively high, this

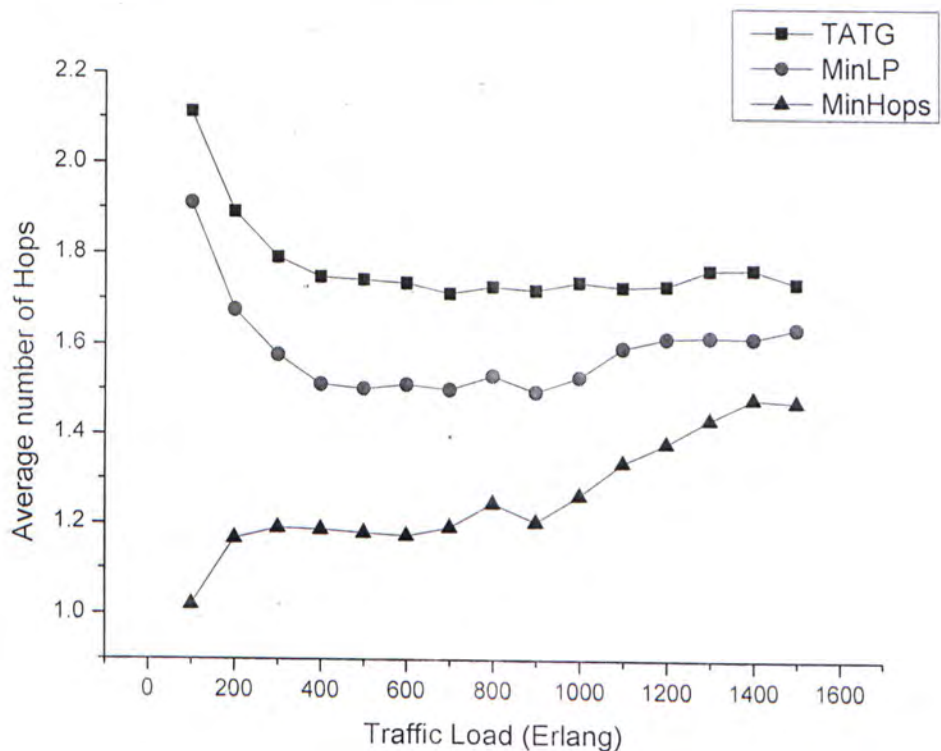


Fig. 3.11: Average number of hops (light-paths) per connection goes through

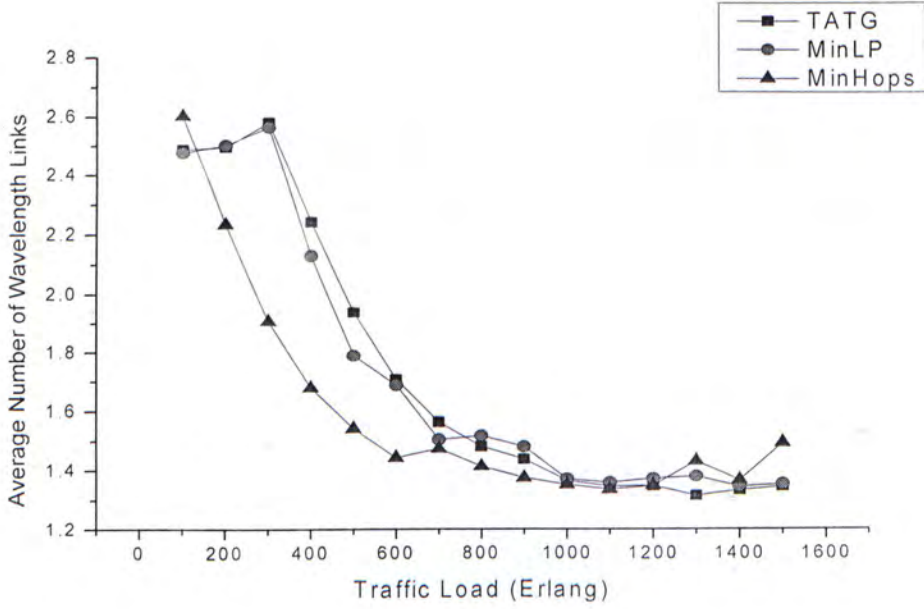


Fig. 3.12: Average number of wavelength links

advantage of TATG diminishes because other policies also groom traffic together intensively in order to accommodate more traffic. In addition, when the traffic load is relatively high, the average number of hops plays an important role in determining energy consumption. When traffic load is even higher, the wavelength resources are highly limited and the three policies would achieve similar energy consumption performances.

Similar to Fig. 3.6, Fig. 3.11 shows the average number of hops (light-paths) per connection request goes through if the three traffic grooming policies are applied. We also observe that MinHops always achieves the least number of hops. The way how average number of hops affects the energy consumption when traffic load is relatively high is the same as before: when traffic load is relatively high, new light-paths are hard to establish for all the three policies. If a connection request goes

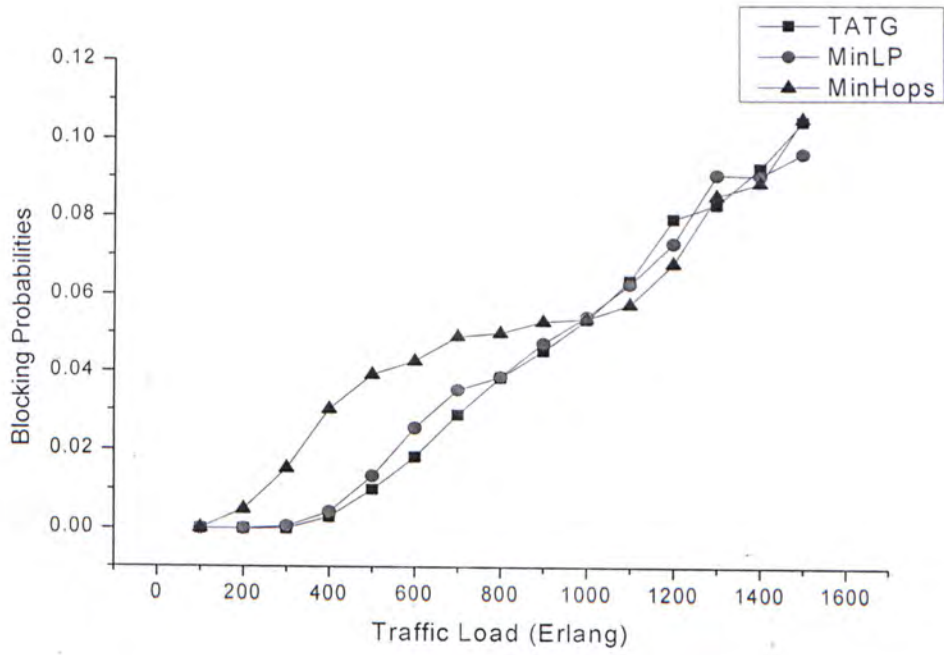


Fig. 3.13: Blocking probabilities

through more existing light-paths (hops), the result is that more light-paths has to carry the traffic of the new connection request and hold for a longer time period, leading to more energy consumption. So this is the reason why MinHops which tries to minimize the number hops consumes the least energy when traffic load is relatively high.

Fig. 3.12 and Fig. 3.13 show the average number of wavelength links per light-path and the blocking probability performances respectively. The results and analysis is quite similar to those of USNET topology.

### 3.5.3 14-node NSFNET:

The 14-node NSFNET shown in Fig. 3.14 is employed for another set of experiments.



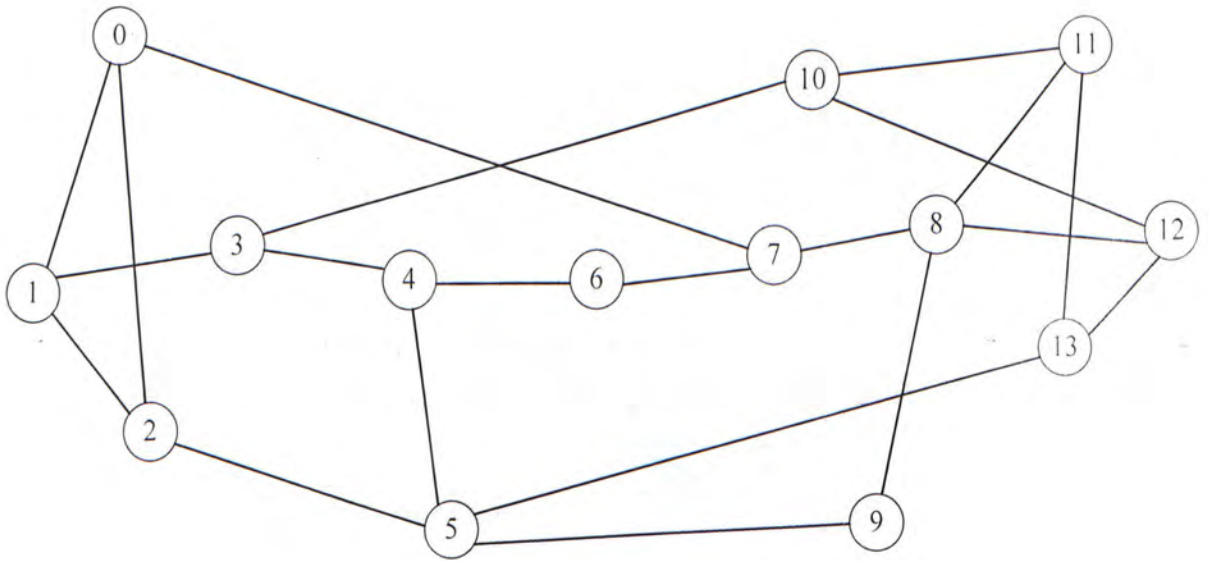


Fig. 3.14: 14-node NSFNET Network

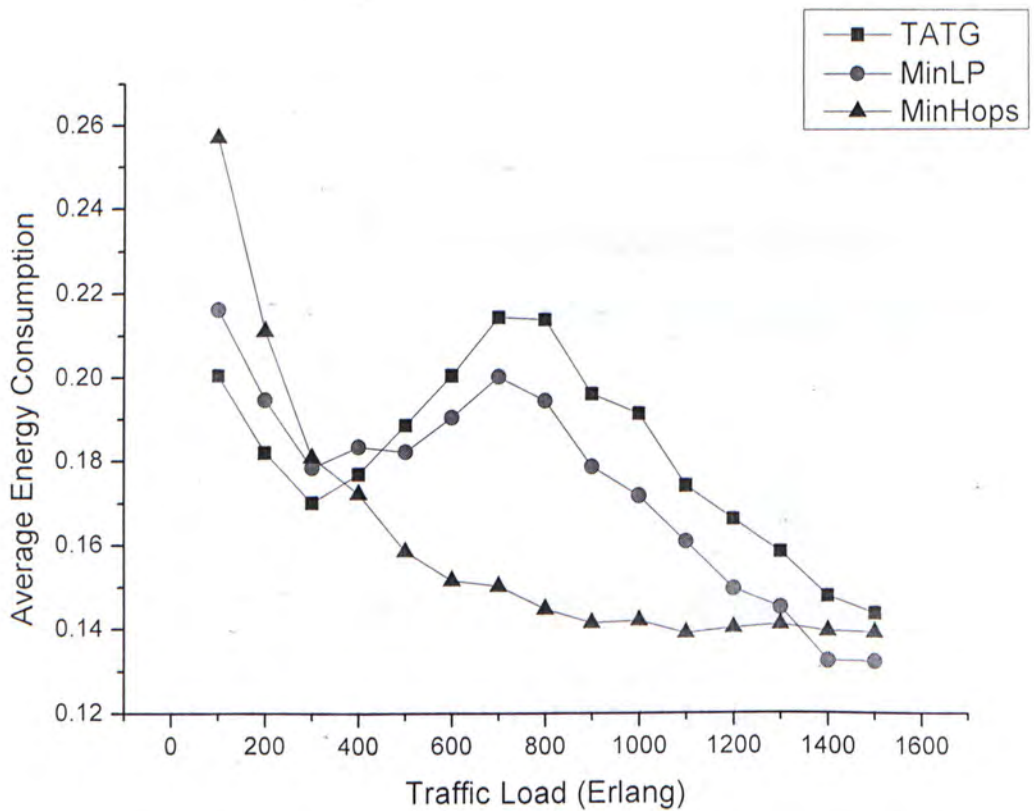


Fig. 3.15: Average energy consumption per connection

Similar to Fig 3.5, Fig. 3.15 shows the energy consumption of the three kinds of

traffic grooming policies under various traffic loads. We observe that TATG achieves the least energy consumption when traffic load is relatively low and MinHops achieves the best performance when traffic load is relatively high. When traffic load is even higher, the three policies would achieve similar energy consumption performances. This is because, when traffic load is relatively low, TATG grooms traffic together as much as possible by trying to route new connection requests through the existing light-paths with longer remaining holding time. On the contrary, MinHops tends to establish new light-paths directly which induces unnecessary energy consumption. However, when traffic load is relatively high, this advantage of TATG diminishes because other policies also groom traffic together

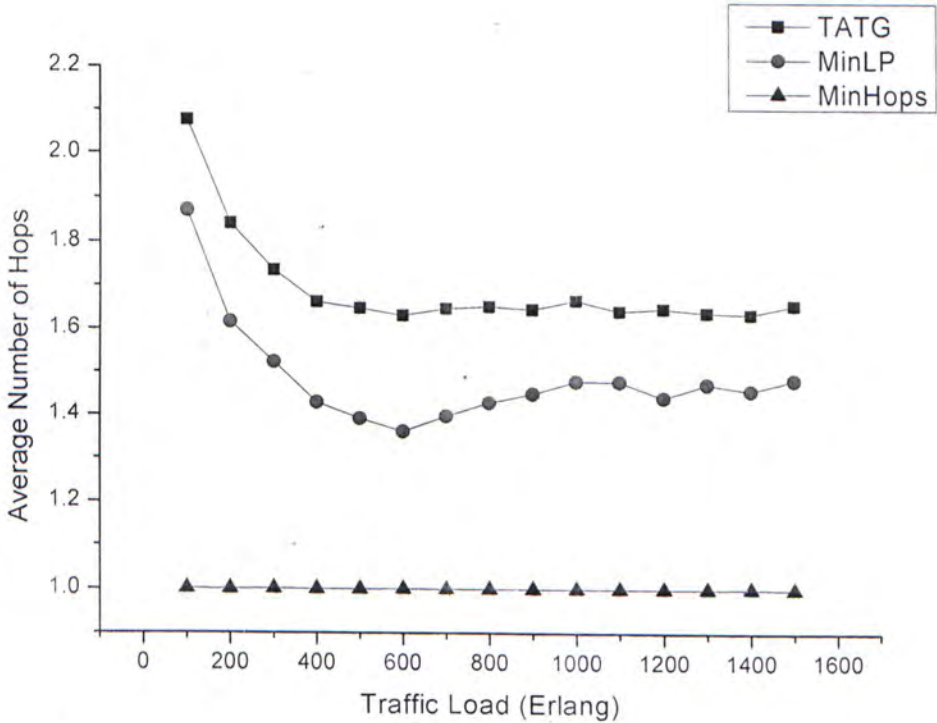


Fig. 3.16: Average number of hops (light-paths) per connection goes through

intensively in order to accommodate more traffic. In addition, when the traffic load is relatively high, the average number of hops plays an important role in determining energy consumption.

Similar to Fig. 3.6, Fig. 3.16 shows the average number of hops (light-paths) per connection request goes through if the three traffic grooming policies are applied. We observe that MinHops always achieves the least number of hops and almost all connection requests can be established using only one hop (light-path). This is because NSFNET topology has less bottleneck links than USNET.

Fig. 3.17 shows the average number of wavelength links per established light-path. TATG and MinLP again achieve similar performance. The difference is that MinHops seems to achieve a constant value. This is because in this topology, almost all connection requests can be established using one hop (light-path). So this constant

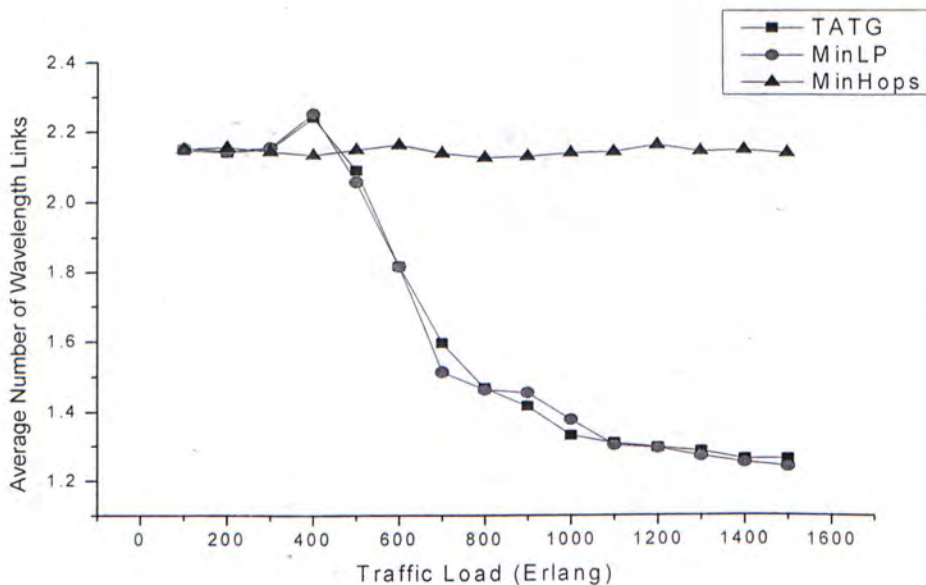


Fig. 3.17: Average number of wavelength links



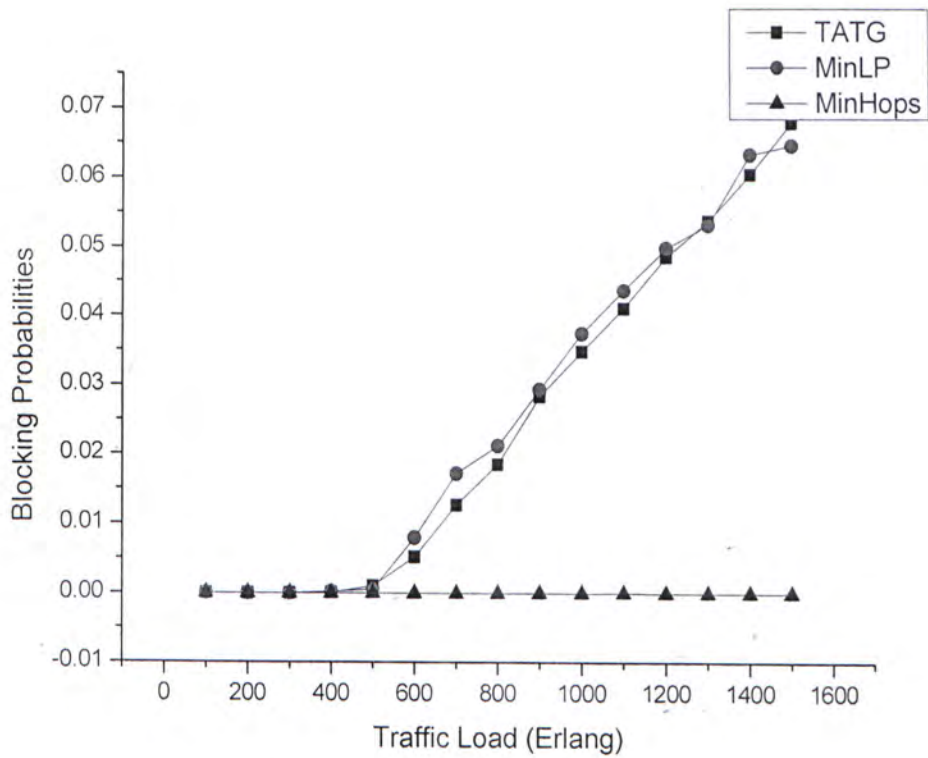


Fig. 3.18: Blocking probability

value is also the average number of fiber links between two random nodes in the NSFNET topology.

As in Fig. 3.8, Fig. 3.18 shows the blocking probabilities of the three kinds of traffic grooming policies. We observe that MinHops achieves nearly zero blocking probability and TATG and MinLP achieve the similar blocking performance. This can be inferred by that, in NSFNET, the bottleneck link effect of MinHops is very small and almost all connection requests can be established using only one hop.

### 3.5.4 Alternative Configuration of Simulation Parameters:

In this sub-section, we will show the simulation results of energy consumption performances under different simulation configurations. We employ the 15-node

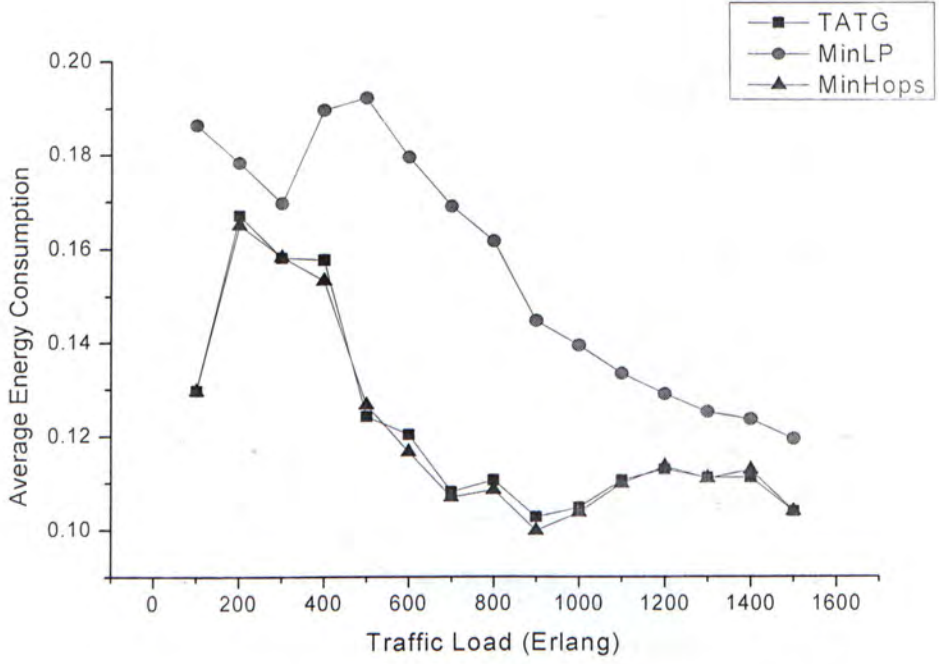


Fig. 3.19: Average energy consumption per connection  $P_0=0$

Pacific Bell network shown in Fig. 3.9 as an example.

Fig. 3.19, Fig. 3.20, Fig 3.21 show the energy consumption of the three kinds of traffic grooming policies under various traffic loads if  $P_0$  is set to 0, 0.76 and 1 respectively. The maximum power consumption of a single light-path is still normalized to 1.

From Fig. 3.19, we can see that when  $P_0=0$ , TATG is actually the same as MinHops. This is because when  $P_0=0$ , the newly induced energy consumption of each connection is related only to the number of hops (light-paths) it would go through. In this case, the holding times of existing lightpaths no longer matters. When  $P_0=0$ , this can be verified from the weight assignments scheme from (3-14)-(3-16) that the weight of transceiver edge is just half of that of the light-path edge and both of their weights are much larger than that of the wavelength edge, which is just the same as

MinHops.

From Fig. 3.20 and Fig. 3.21, we can observe that as  $P_\theta$  is approaching 1, MinHops

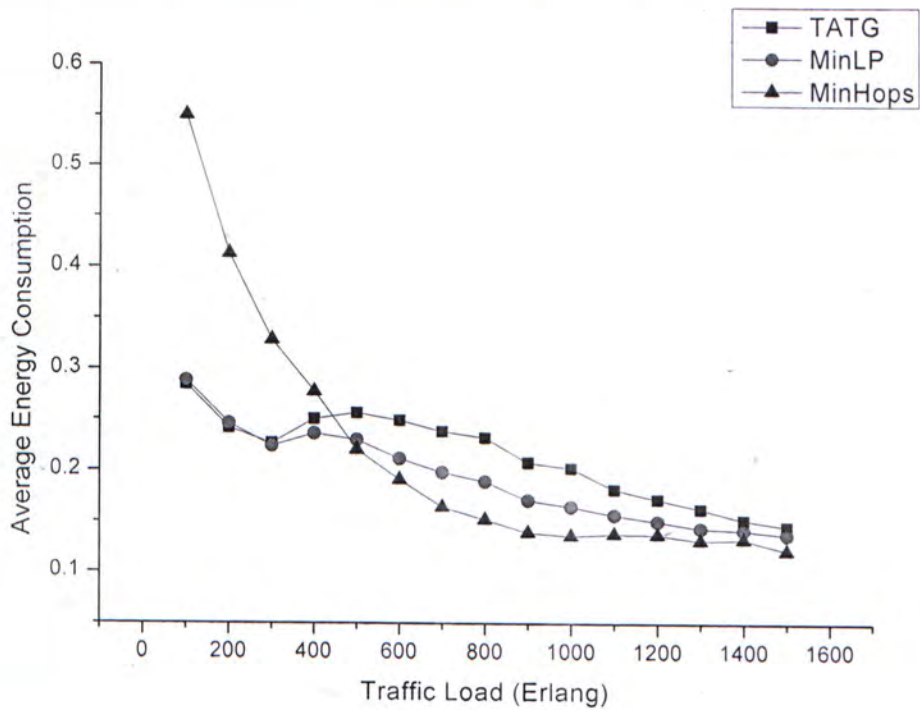


Fig. 3.20: Average energy consumption per connection  $P_\theta=0.76$

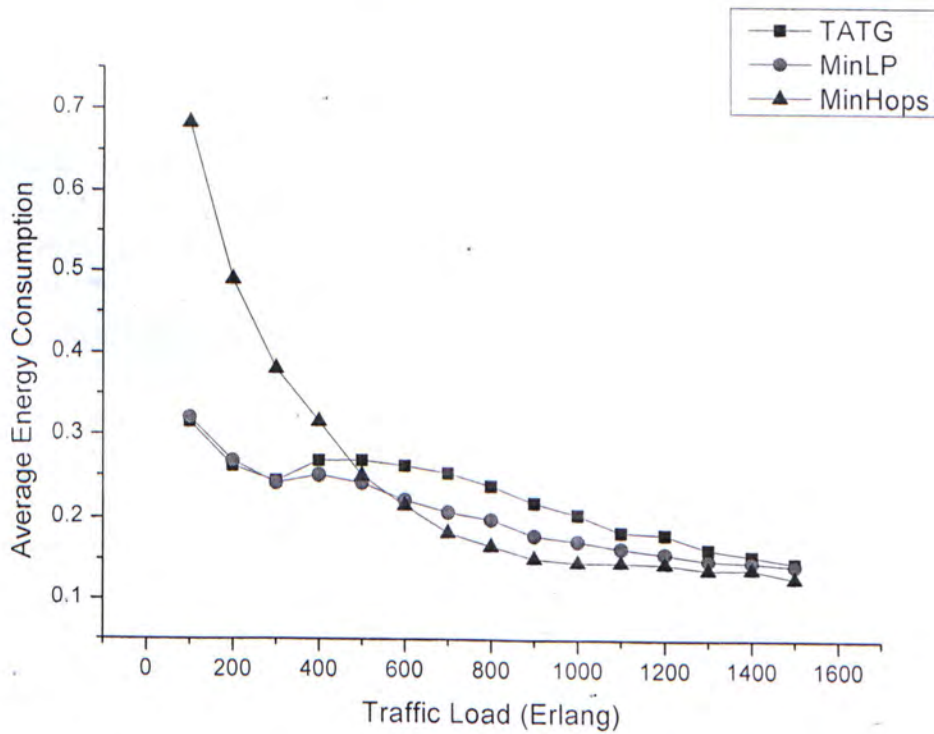


Fig. 3.21: Average energy consumption per connection  $P_\theta=1$



performs much worse when traffic load is relatively low. This is because the main energy consumption is due to the newly established light-paths. When traffic load is low, MinHops would rather establish new light-paths than going through several existing lightpaths to reduce the hop distances. Similar to the reasons when  $P_0=0.25$ , when traffic load is relatively high, MinHops achieves the best performance among the three policies because the average number of hops plays an important role when traffic load is high.

Fig. 3.22 shows the performance when  $P_0=0.76$  and the granularity of a connection request is uniformly distributed between OC-1 and OC-96. (The traffic load of 500 Erlang is relatively large in this case because the blocking probability is around 30% under this traffic load). We can still observe that TATG performs the best when traffic load is relatively low and MinHops achieves the best performance among the

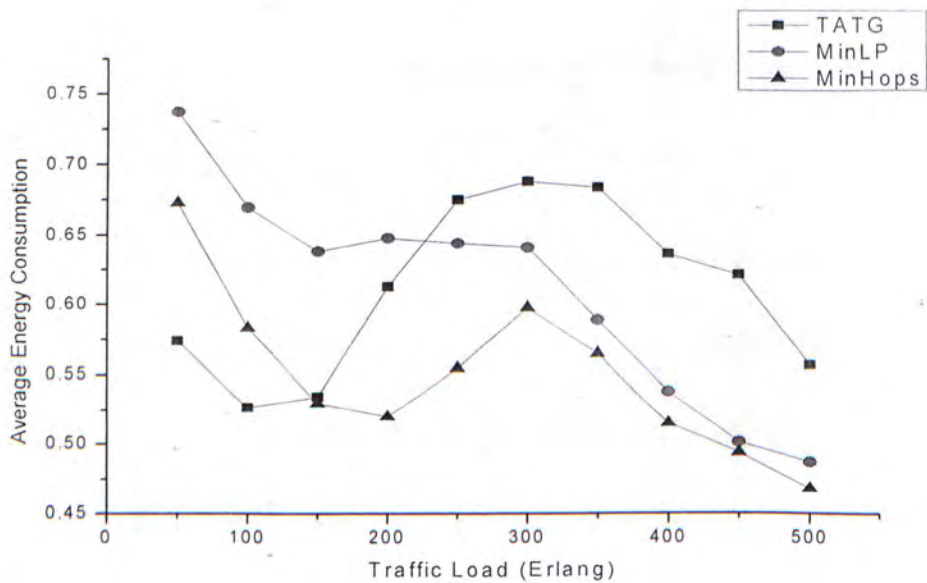


Fig. 3.22: Average energy consumption per connection  $P_0=0.76$  and connection uniformly distributed between OC-1 and OC-96

three policies when traffic load is relatively high.

According to the simulation results under different parameter configurations, implications can be provided to choose the most energy-efficient grooming policies under various traffic loads. We can adopt an adaptive scheme in which TATG is employed when traffic load is relatively low and MinHops is employed when traffic load is relatively high. The exact threshold of traffic load can be determined according to network topology and traffic characteristics.

### **3.6 Summary**

Both static and dynamic time-aware traffic grooming problems are studied in order to reduce the energy consumption. Minimizing power consumption may not necessarily lead to minimizing energy consumption. So time information is very important and should be taken into consideration in energy efficient design. According to the simulation results, TATG can achieve the least energy consumption when traffic load is relatively low and MinHops can achieve the least when traffic load is relatively high. But when traffic load is even higher, the three traffic grooming policies would achieve similar performance in terms of energy consumption.

# Chapter 4 Conclusions and Future Work

## 4.1 Conclusions

Multicast protection and energy-efficient traffic grooming in wavelength-routing networks have been addressed in this thesis, with respect to the time information of traffic and network resources.

Multicast tree protection with scheduled traffic has been formulated and numerically investigated under different traffic models. First, an ILP formulation has been presented to minimize the total costs of establishing all multicast sessions under FSTM. The results have shown that the network resources can be jointly optimized both in space and time to provision survivable multicast sessions at much lower costs, compared to the previous schemes which are unaware of the traffic time information. Second, a two-step optimization approach has been adopted to deal with the survivable multicast provisioning problem under SSTM. Thus, the survivable multicast sessions can be provisioned at much lower costs.

Minimizing power consumption may not necessarily lead to minimizing energy. So time information is very important and should be taken into consideration in energy efficient design. Both static and dynamic time-aware traffic grooming problems are studied in order to reduce the energy consumption. In static case, all connection requests with their setup and tear-down times are known in advance, we formulate an Integer Linear Programming (ILP) to minimize the energy consumption. In dynamic



case, we adopt a layered graph model called Grooming Graph and propose a new traffic grooming heuristics called Time-Aware Traffic Grooming (TATG) which takes the holding time of a new arrival connection request and the remaining holding time of existing light-paths into consideration. We compare the energy efficiency of different traffic grooming policies under various traffic loads and investigate various parameters such as average number of hops and average number of wavelength links to find the causes of energy variation. The results provide implications to choose the most energy-efficient traffic grooming policies under various scenarios.

## 4.2 Future Work

First, Although ILP can find the optimal solutions to the multicast protection problem with scheduled traffic, it would require large amount of running time in the scenario where a large network or heavy traffic load is applied. As a result, our future works will focus on investigating heuristics on finding the optimal RWA of survivable multicast sessions with scheduled traffic.

In addition, energy-efficient traffic grooming is considered under the assumption that the provisioning periods of the connection requests are only determined by the users' requests. If network operators are given the right to schedule the connection requests, better energy efficiency may be achieved.

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## **Publications during M.Phil Study**

### **Published or accepted:**

- [1] S. Q. Zhang, D. Shen, C. K. Chan, "Energy Efficient Time-Aware Traffic Grooming in Wavelength Routing Networks," in *GLOBECOM 2010*, Miami, USA, Dec. 2010.
- [2] S. Q. Zhang, C. K. Chan, "Multicast Protection in WDM Optical Networks with Scheduled Traffic," in *Proc. European Conference on Optical Communications, ECOC 2009*, Paper P5.06, Vienna, Austria, Sep. 2009.
- [3] D. Shen, S.Q. Zhang, C.K. Chan, "Design of Translucent Optical Network using Heterogeneous Modulation Formats," in *Proc. OptoElectronics and Communications Conference, OECC 2010*, Paper 8P-09, Sapporo, Hokkaido, Japan, 2010.

### **In submission:**

- [1] S.Q. Zhang, C. K. Chan, "Provisioning of Survivable Multicast Sessions in Wavelength-routed Optical Networks with Scheduled Traffic, submitted to *Journal of Lightwave Technology*.





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