TRAFFIC LIFETIME-AWARE ROUTING CONSIDERING DYNAMIC GROOMING IN WDM NETWORKS

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A THESIS SUBMITTED

FOR THE DEGREE OF MASTER OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2004

Acknowledgment

I am extremely grateful to Dr. Yuming Jiang, my research supervisor and thesis advisor, for giving me guidance and encouragement during my graduate studies. From the very beginning, he treated me as a friend and gave me right amount of freedom for my research. He kept on catching me in the research progress, gave me many advices about the research problem and taught me the art of making science research in detail. For skills to write articles, Dr. Yuming Jiang helped me to improve the logical structure of my papers and to express my ideas and solutions more rigorously. He suggested me to find multiple ways to prove and explain my results, which could make my ideas more reasonable. Most of all, he gives me trust and great encouragement all along, without which, the research process would be a very painful time for me.

I am indebted to my husband for giving me self-giving and strong support to finish the research. With his dedication and love, I can securely carry through the study. He also discussed technical problems with me and provided me some advices on the research topic. During the two years, he was an invaluable source of feedback and motivity. Without his effort, it would not have been possible to reach this stage in my career.

Thanks to Dr. Shengming Jiang. He awoke me how to go on with my research and simulation when I was facing a stubborn coding problem. He even tried his best to help me finish this thesis in the case that Dr. Yuming Jiang is not convenient to guide me.

I am grateful to all my friends, especially Zheng Wu, Haiming Xiao, Zhe Liang and Lei Xiao for their feedback and for their advice that helped to shape my research skills. They helped me much by discussing research issues and giving me excellent feedback after reading drafts of my articles. Luqing Yang helped me several times to solve some simulation problems. With Zita and Teh KengHoe, I have improved my English writing skills. In addition, thanks to my other friends, Licheng Guo, Erji Wang, Yan Sun, Badri, Hui Hua, Qing Gao, Jing Xie, Qunying Xie, Qijie Huang, Nan Li, Hai Long, Jianfeng Li, Chun Nie and Hua Wen. I had so much joy and happiness with them during our moments together.

Finally, thanks to other members in my family. Their love to me makes me so fortunate.

Contents

Summary

This thesis presents a lifetime-aware scheme for routing considering dynamic grooming for WDM mesh networks, which is adaptive to the lifetime of traffic flows and resource utilization on the virtual topology. Although routing and grooming sound to be independent, they are actually closely related particularly at the virtual topology. In this scheme, routing decision is combined with dynamic grooming policy adaptive to resource utilization at virtual topology with the objective to minimize the blocking probability of connection requests. Paths are selected among a candidate set of paths chosen by the grooming policy and utilization of some resources is referred as constraints. Moreover, since lightpath is logical link in virtual topology, in the case of multiple lightpaths existing between a node pair, grooming policy can help routing algorithm to choose one logical link from multiple logical links connecting the same node pair.

As suggested in the scheme, grooming policy and routing decision can take lifetime of traffic session into account. A lot of research work shows that although the "long-lived" flows just occupy a very small ratio of all the traffic flows in the Internet, they account for a high proportion of packets (bytes) on a link. Viewing this, we conduct grooming and routing considering this traffic characteristic by classifying flows as short-lived and long-lived.

Thus, different services are provided to these flows to produce better resource utilization.

Simulation results show that the proposed scheme is adaptive to dynamic network states and can get better usage of resources. As a result, lower blocking probability and higher wavelength utilization are achieved as compared to some benchmark schemes.

Keywords: Dynamic Grooming, Resource Utilization, Traffic Lifetime, WDM Mesh Network

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Abbreviations

WDM:	**Wavelength-Division Multiplexing**
OADM:	**Optical Add/Drop Multiplexer**
OXC:	**Optical Crossconnect**
WRR:	**Wavelength Add/Drop Multiplexer**
WXC:	**Wavelength Crossconnect**
MPLS:	**Multiple Protocol Label Switching**
GMPLS:	**Generalized Multiple Protocol Label Switching**
CIDR:	**Classless Inter-Domain Routing**
RWA:	**Routing and Wavelength Assignment**
SLE:	**Static Lightpath Establish**
DLE:	**Dynamic Lightpath Establish**
ILP:	**Integer Linear Problem**
RF:	**Random Fit**
FF:	**First Fit**
LU:	**Least Used**
MU:	**Most Used**
MP:	**Min Product**
LL:	**Least Loaded**
MS:	**Max Sum**

RCL:	**Relative Capacity Loss**
SDM:	**Space-Division Multiplexing**
TDM:	**Time-Division Multiplexing**
DWG:	**Dedicated-Wavelength Grooming**
SWG:	**Shared-Wavelength Grooming**
OADM:	**Optical Add/Drop Multiplexer**
WADM:	**Wavelength Add/Drop Multiplexer**
DXC:	**Digital Crossconnect**
BI:	**Blocking Island**
WO:	**Wavelength Occupancy**
OSPF:	**Open Shortest Path First**
MURT:	**Routing with Regard to Most-Used Grooming Policy**
MURT-LL:	**MURT for Long-Lived Traffic**

Chapter 1

Introduction

1.1 WDM Networks

As the explosive growth of Internet traffic, current traffic patterns are much more abundant than before, which include high bandwidth applications such as multimedia, video conferencing, medical imaging and supercomputer visualization. As a result, the need for very high speed networks (Tb/s) raises greatly. Optical network implemented using *wavelength-division multiplexing* (WDM) techniques, called *wavelength-routed optical network* (WDM network), has emerged as an efficient technology for exploiting the huge bandwidth capacity inherent in optical fibers. A single fiber strand has the potential bandwidth of 50 THz. Using WDM, the bandwidth can be divided into multiple non-overlapping frequencies or wavelength channels. The idea is to transmit data simultaneously on different channels over the same fiber. Each WDM channel can be operated at any possible speed, e.g., peak electronic speed of a few gigabits per second (Gbps). Currently, bit rates are usually 2.5Gb/s or 10 Gb/s on each channel and higher speed can be achieved commercially in the near future.

In the recent years, it has been realized that optical networks are capable of providing more functions than just point-to-point networks. Thanks to the rapid advances in optical components, some of the switching and routing functions that have been performed by electronics before can now be performed in the optical part of the networks, which, has enabled the transition from point-to-point WDM links to all-optical networking. The key network components in optical networks are *optical line terminals* (LTs), *optical add/drop multiplexers* (OADMs) and optical *crossconnects* (OXCs). The corresponding elements in WDM networks are *optical line terminals* (LTs), *wavelength add/drop multiplexers* (WADMs) and *wavelength crossconnects* (WXCs). A LT multiplexes multiple wavelengths (say W) into a single fiber and demultiplexes a set of wavelengths (W) on a single fiber into separate fibers. Such a LT is deployed at either end of a point-to-point link and requires W transponders or W wavelength ports (transmitters and receivers). WXCs take in signals at multiple wavelengths and selectively drop some wavelengths locally, while allowing others bypassing optically (no optical-electric-optical conversion) between a fixed input fiber and output fiber. A WXC essentially performs similarly as a WADM while the former can additionally switch a wavelength possibly from any input fiber to any output fiber. As shown in Figure 1.1, a WDM wavelength-routed network consists of multiple WXCs connected by a set of fiber links to form a mesh topology [1].

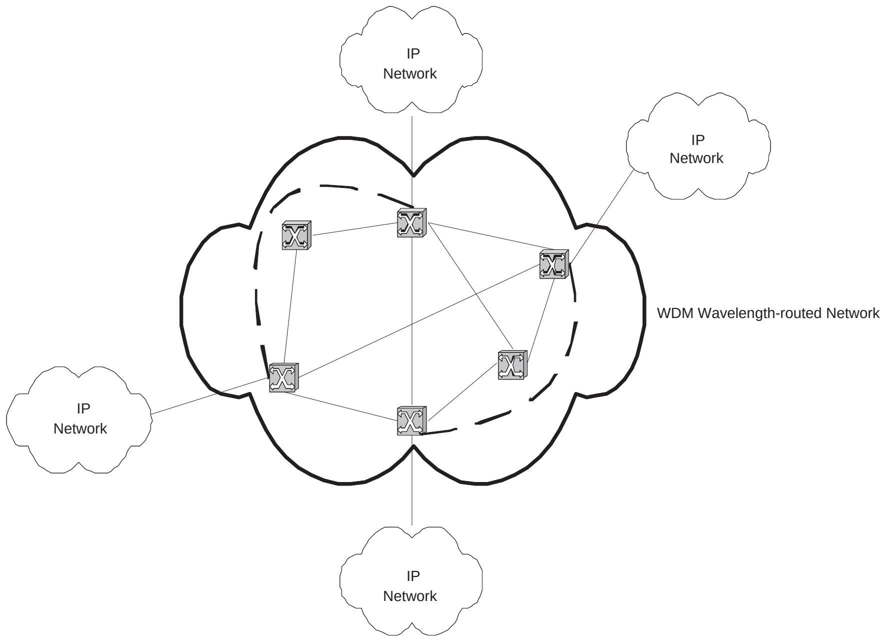


Figure 1.1: Illustration of a Wavelength-Routed Networks

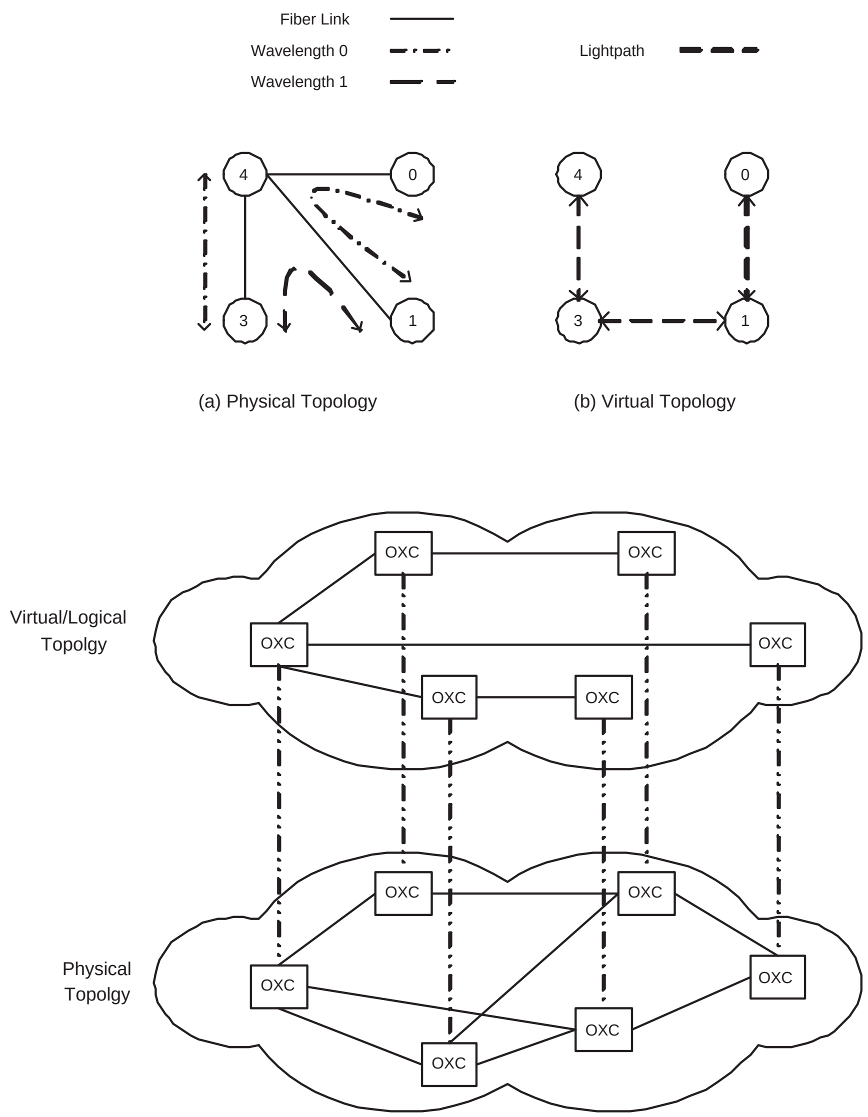
The concept of wavelength routing is the basis for future all-optical wide-area WDM networks. The services that a wavelength-routed network provides to its client subnetworks are in the form of *virtual or logical topology* implemented by wavelength channels called lightpaths. A lightpath is uniquely identified by a physical route and a set of wavelengths without optical-electric-optical (o-e-o) conversion or buffering at intermediate nodes. A wavelength-routed networks is also referred to as an *all-optical network*. It provides a "circuit-switched" interconnection between two nodes on the physical fiber network topology. Different lightpaths in a wavelength-routed network can use the same wavelength as long as they do not share any common link. Thus, wavelengths can be reused spatially in different parts of the network. There are two types of all-optical networks, namely, wavelength-routed networks with wavelength conversion and wavelength-routed networks without wavelength conversion. In a wavelength-routed network without wavelength conversion, a lightpath can be established only if the same wavelength is available on every hop between the source and destination nodes. This is the *wavelength continuity constraint*. This constraint may be relaxed if a switching/routing node is equipped with wavelength-converter facility.

Wavelength converter is a single input/output device that converts the wavelength of an optical signal arriving at its input port to a different wavelength when the signal departs from its output port. Wavelength conversion allows a lightpath to use different wavelengths on different links along the path. Some levels of wavelength conversion capability are possible. A WXC with *full wavelength conversion* capability can convert any input wavelength to any other wavelength at the output port. *Limited wavelength conversion* capability implies that each input wavelength can be converted to any of a specified set of wavelengths. *Fixed wavelength conversion* is applied to convert one wavelength to exactly another wavelength. *Degree of wavelength conversion* (D) refers to that one wavelength can be converted to any of D wavelengths. Wavelength conversion makes more efficient use of wavelengths, resulting in better network performance. However, converter is expensive and the use of converters increases network cost and complexity of operation. *Sparse conversion networks* can be constructed if the wavelength conversion capability is available in a relatively small fraction of nodes. For a multi-fiber WDM network, a bundle of F fibers may exist on a single link using space-division-multiplexing and each fiber may carries W wavelengths. In this network, wavelength continuity constraint is overcome to a certain extent because it is equivalent to a single-fiber network with each fiber carrying $F * W$ wavelengths and each node having wavelength conversion capability of degree F.

A WDM wavelength-routed network can be viewed as a two-layer infrastructure. The lower layer is *physical topology* and the upper layer is *virtual/logical topology* [2]. A physical topology is a graph representing the physical interconnection of the wavelength-routed nodes by means of fiber-optic cables. A logical topology is a directed graph that results when the set of lightpaths over the physical network create a logical (or virtual) topology among the nodes (as shown in Figure 1.2). Its set of nodes is the same as the physical topology and its edges, also called logical links, are the lightpaths [2]. When making routing decision for such a WDM wavelength-routed network, connection requests usually only take the virtual topology into consideration without knowing of how the physical layer is constructed.

1.2 Integration Strategies for IP Over WDM

As WDM technology has dramatically enhanced the capacity of fiber links, electronic switching in network layer becomes the main bottleneck opposed to bandwidth. The trend for the core network is to be simpler and faster. As a result, the efficient interworking of higher layer protocols, most notably IP, over WDM networks is a key issue.



(c) A WDM wavelength-routed network can be viewed as a two-layer infrastructure

Figure 1.2: Illustrative Example of Virtual Topology

An optical control framework is necessary for close integration between physical networks and higher-layer networking protocols such as IP. Until recently, most studies on optical interworking have focused on the "optical-layering" approach, which means to develop a special layer between the physical layer and the higher layer to construct a framework for operations, administration, management and provisioning [3]. This approach can provide basic functions such as lightpath channel routing and maintenance, network survivability capability, fault detection/localization and addressing issues as well [4]. However, since an additional layer can add cost and complexity for operation, a novel approach for direct integration of IP and physical layer is introduced as generalized multiple protocol label switching (GMPLS) [5]. This approach generalizes the use of multiple protocol label switching (MPLS) [6] concept to incorporate optical lightpath channels. The two frameworks of optical-layering and GMPLS are compared in [4] and are illustrated in Figure 1.3.

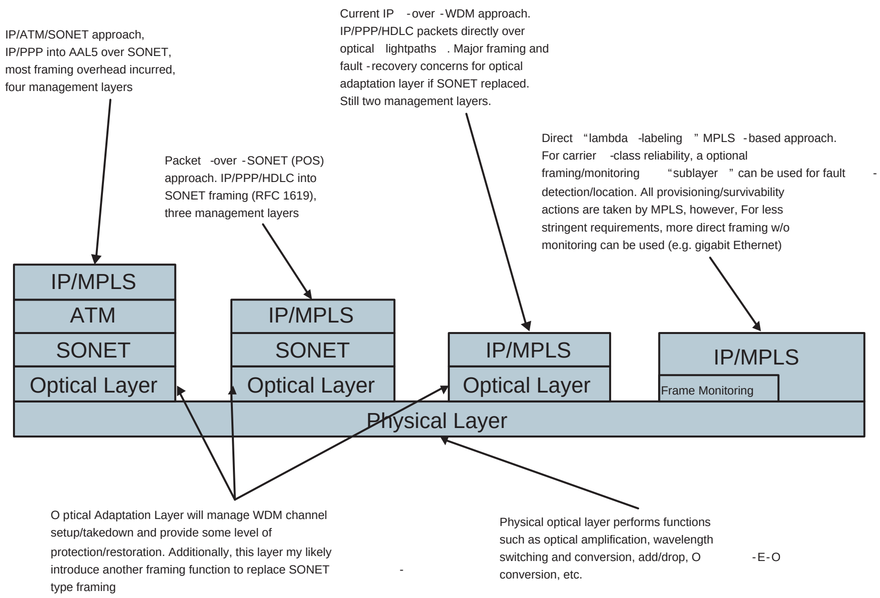


Figure 1.3: Integration schemes for IP over WDM, optical-layering and GMPLS approaches

In this thesis, optical layering approach is assumed as the integration strategy for IP over WDM networks. In this approach, WDM networks can be viewed as a two-layer framework consisting of physical topology (on the physical layer) and virtual topology (on the optical layer) that is composed of multiple lightpaths. In WDM networks, when a connection request arrives, the *routing* process is first implemented to find paths on the virtual topology. Then, the *grooming* policy, which refers to the operation of aggregating multiple low-speed flows onto high-capacity WDM channels or lightpaths [7], is applied to groom the traffic from the request to existing lightpaths. If no existing lightpath is available to accommodate the request, *routing and wavelength assignment (RWA)* algorithm is used to establish a new lightpath on the physical topology according to some network constraints. Consequently the virtual topology is updated and the *routing* process can proceed to select routes to meet the request. This work flow is illustrated in Figure 1.4.

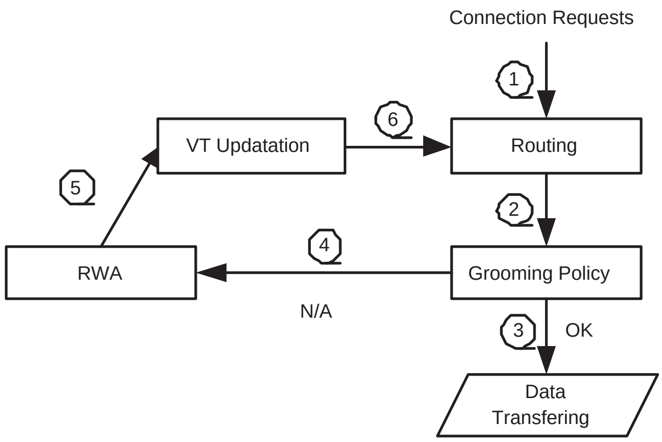


Figure 1.4: Work flow of packet routing on a WDM Network: (1) Requests arrive. (2) Grooming policies are applied for routing decision. (3) If grooming is successful, begin data transmission. (4) If no enough existing lightpath available, using routing and wavelength assignment(RWA) algorithm to setup new lightpaths. (5) Virtual topology is updated. (6) Routing decision is made again according to the updated virtual topology

1.3 Literature Review

1.3.1 Routing and Wavelength Assignment (RWA)

As mentioned above, in WDM networks, lightpaths can provide direct connection channels between non-adjacent nodes. It is generally desirable to establish lightpaths between every pair of nodes. However, some physical constraints, such as wavelength channel spacing in fiber links and limited number and tunability of optical transceivers, limit the total number of usable channels, resulting in that the number of wavelengths available on each fiber link limits the number of end-to-end connections [8]. Given the wavelength continuity constraint and the *distinct wavelength constraint* that all lightpaths using the same fiber link must be allocated distinct wavelength, it is necessary to determine both the routes over which these lightpaths should be established and the wavelengths that should be assigned to these lightpaths on the physical topology. This problem is known as the routing and wavelength assignment (RWA) problem. The RWA problem can be classified into two types according to the traffic assumptions [8]: 1) the *static* RWA problem, wherein a set of connection requests are known in advance. The objective of static RWA is to establish lightpaths for these requests using minimum network resources such as the number of wavelengths and the number of fibers. Alternatively, the objective is to maximize the number of lightpaths given a limited number of wavelengths per link. 2) the *dynamic* RWA problem wherein the connection requests arrive to and depart from the network in a random manner. The target of dynamic RWA is to minimize the blocking probability of the network.

RWA problem is a dual problem and is typically partitioned into the lightpath routing sub-problem and the wavelength selection sub-problem. While the former is to determine the physical links for the lightpaths, the latter is to assign wavelengths to these lighitpaths. Although attempting to solve the subproblems and combining the solutions may result in a suboptimal solution or even no solution to the RWA problem, this is a commonly used approach, since exact solution of RWA may not be possible due to the fact that the two subproblem are both NP-hard.

Lightpath Routing

The solutions for lightpath routing can be classified into three types [9]: fixed routing, alternate routing and exhausted routing. Fixed routing provides one route for a node-pair which is pre-determined and fixed. It is simple but may have poor performance. In alternate routing, a number of routes are pre-computed for a node-pair, so that flows can search the routes one by one to choose paths. Usually, performance increases when the number of alternative routes increases. In exhausted routing, the network is represented as a graph and a shortest path algorithm is used. The best path is selected from all possible routes. Algorithms belonging to this class generally have better performance than the previous two solutions.

The solutions can be further divided into two components 1) search and 2) selection functions [8]. The search function is usually performed by the shortest-path algorithm and its variations (e.g. weighted shortest path and

k-shortest path [8]. The selection functions can be performed on the basis of search rules. Some typical search rules are random scheme, probability schemes, longest-path-first and shortest-path first. [10][11][12][13] are examples of shortest-path-searching algorithms without selection functions.

Wavelength Assignment

Similar to RWA, wavelength assignment algorithms can be either static for static lightpath establishment problem (SLE) or dynamic for dynamic lightpath establishment problem (DLE) [9].

For static wavelength assignment (WA), it is assumed that lightpaths and their routes are known in advance and different lightpaths are assigned different wavelengths on any given fiber link. The static WA can be solved by formulating the problem as either integer linear problem (ILP) or sequential graph-coloring problem [8]. In addition, some heuristic algorithms are studied, e.g. largest-first and smallest-last algorithms [14]. These two algorithms are based on node degree which is defined as the number of links connected to the node in an undirected graph. Given the lightpaths and their routes, a graph $G(V, E)$ is constructed such that each lightpath is represented by a node in graph G. In the largest-first approach, the vertices $V(G) = v_1, v_2, ..., v_n$ are ordered such that $degree(V_i) \geq degree(V_{i+1})$, for $i = 1, 2, 3, ..., n-1$, where n is the number of nodes in the graph G. At each step, the nodes with highest degree are assigned a color and the corresponding links are deleted, thus reducing the degree of adjacent nodes. As a result, at each step, the degree of some nodes decreases. This ensures that minimum number of colors is used to color the graph. In smallest last approach, the vertices $V(G) = v_1, v_2, ..., v_n$ are ordered such that $degree(V_i) \leq degree(V_{i+1})$.

Dynamic WA also assumes that a fixed number of wavelengths exists for allocation. However, unlike static WA, dynamic WA does not require the route of each lightpath to be known a priori. As a consequence, the objective of dynamic WA is to minimize connection blocking probability for establishing lightpaths. Some known heuristic algorithms for dynamic WA include: Random-Fit (RF), First-Fit (FF), Least-Used (LU), Most-Used (MU), Min-Product (MP), Least-Loaded (LL), Max-Sum (MS), Relative Capacity Loss (RCL) and etc [14]. Among these algorithms, random-fit and least-used aim to balance the traffic load on each wavelength. LU can be viewed as the extreme application of RF. Using RF, a wavelength is randomly selected with uniform probability distribution from a set of available wavelengths. And using LU, a wavelength that has been used the least is selected for a connection. As for fairness, LU can be regarded as the fairest case of RF. In the first-fit scheme, wavelengths on each fiber link are numbered. The lowest numbered wavelength is selected to establish a new lightpath. Furthering the idea of FF is the MU scheme in packing the use of wavelengths. It select the most-used wavelength for the next assignment. In max-sum scheme, all possible paths are considered and the aim is to maximize the remaining path capacities after lightpath establishment. Traffic matrix is assumed to be known in advance in this scheme. RCL calculates the relative capacity loss for each path on each available wavelength, and chooses the wavelength which can minimize the sum of RCL on all the paths. RCL can solve the problem that minimizing the total capacity loss sometimes does not lead to best choice of wavelength. As a result, it outperforms MS scheme. Min-product and least-loaded are applied in multi-fiber networks. Heuristic of MP selects a wavelength to minimize the number of fibers being occupied at a time. Heuristic of LL aims to maximize the residual capacity for the most-loaded link along a route.

The above schemes are heuristics and the approximate order of increasing performance is LU, RF, MP, FF, MU and LL [14].

1.3.2 Traffic Grooming

In order to use resource efficiently and minimize network cost, it is required to multiplex or aggregate multiple low-speed data streams onto high-capacity channels. This technique is called *traffic grooming*. Different multiplexing techniques can be used for traffic grooming in different domains of optical networks [15]. One is *Space-division multiplexing* (SDM) in which the different spatial position determines a channel-routing path, e.g. lighting up additional fibers or deploying additional fibers as needed. Another traditional approach is *Time-division multplexing* (TDM). It is a method of putting multiple data streams in a single channel by separating the channel into many segments, each having a short time duration. Each individual data stream is reassembled at the receiving end based on the timing. A third approach is *wavelength-division multiplexing* (WDM) as introduced earlier. This approach allows different wavelengths to carry data at different bit rates and protocol formats. As a result, WDM provides great flexibility to build optical networks.

Currently an optical fiber can support over a hundred wavelength channels each of which can transmit at a speed of over a gigabit per second (e.g., OC-12, OC-48, OC-192 and etc.) However, the network may transmit traffic of much lowe rate varying in the range from STS-1 (51.84 Mbps or lower) to full wavelength capacity. One efficient approach to provide fractional wavelength capacity is to divide a wavelength channel into multiple time slots and multiplex data streams on the wavelength. This WDM time-division multiplexing technique is referred to as WDM-TDM and a network using WDM-TDM is called as *WDM grooming network* [16]. In such a network, each node can multiplex/demultiplex as many as possible low-rate data streams onto a wavelength channel and traffic is switched internally at much finer granularities such as STS-1.

In a WDM grooming network, each node contains a *wavelength crossconnect* (WXC) to support traffic grooming. The ratio of the wavelength-channel rate to the lowest traffic rate is known as the *grooming ratio*.

WDM grooming networks can be classified into two categories [16]: (1) dedicated-wavelength grooming (DWG) networks and (2) shared-wavelength grooming (SWG) networks. In a DWG network, pairs of source and destination nodes are connected by lightpaths onto which traffic flows are multiplexed. Once no enough bandwidth of any lightpath is available for a new connection request, a new lighitpath from the source to the destination has to be established for the request. This grooming scheme is called *single-hop traffic grooming*. On the other hand, in a SWG network, if a new request cannot be accommodated by any existing lightpath to the destination, it would be multiplexed onto a lighitpath to an intermediate node. The connection is then switched from the intermediate node to the destination node either directly or through other nodes. This scheme is called *multi-hop traffic grooming*. The performance of a WDM grooming network depends on the efficient merging of low-speed connection requests to full or almost-full wavelength requirements.

In a DWG or SWG network, grooming can be either static or dynamic. In static grooming, the source-and-destination pairs of data streams are predetermined. Hence, grooming decision can be made considering the distribution of connection requests over the network. In dynamic grooming, connection requests come and depart in a random manner and grooming decision is done at the time of request arrival.

As the WDM networks grow from SONET ring networks to irregular WDM mesh networks, an increasing amount of research activities has focused on traffic-grooming problems.

Grooming in SONET/WDM Rings

SONET/WDM ring is widely used today as the most popular optical network infrastructure. Electronic add-drop multiplexers (ADMs) are used to add/drop traffic at intermediate nodes to/from the high-speed channels. In a traditional SONET ring network, nodes are equipped with optical add/drop multiplexers (OADM) (also referred to as wavelength add/drop multiplexers (WADM)) as shown in Figure 1.5 (a), it is possible for a node to bypass most of wavelength channels optically and only drop the wavelengths carrying the traffic intended for the node.

If a node has a *Digital-Crossconnect* (DXC) (as shown in Figure 1.5(b)) installed, it is called a hub node. Traffic from one wavelength/time-slot can be switched to any other wavelength/time-slot at a hub node. In this case, a lightpath needs to be terminated by transceivers and its traffic is converted to electronic form for wavelength/time-slot exchanging.

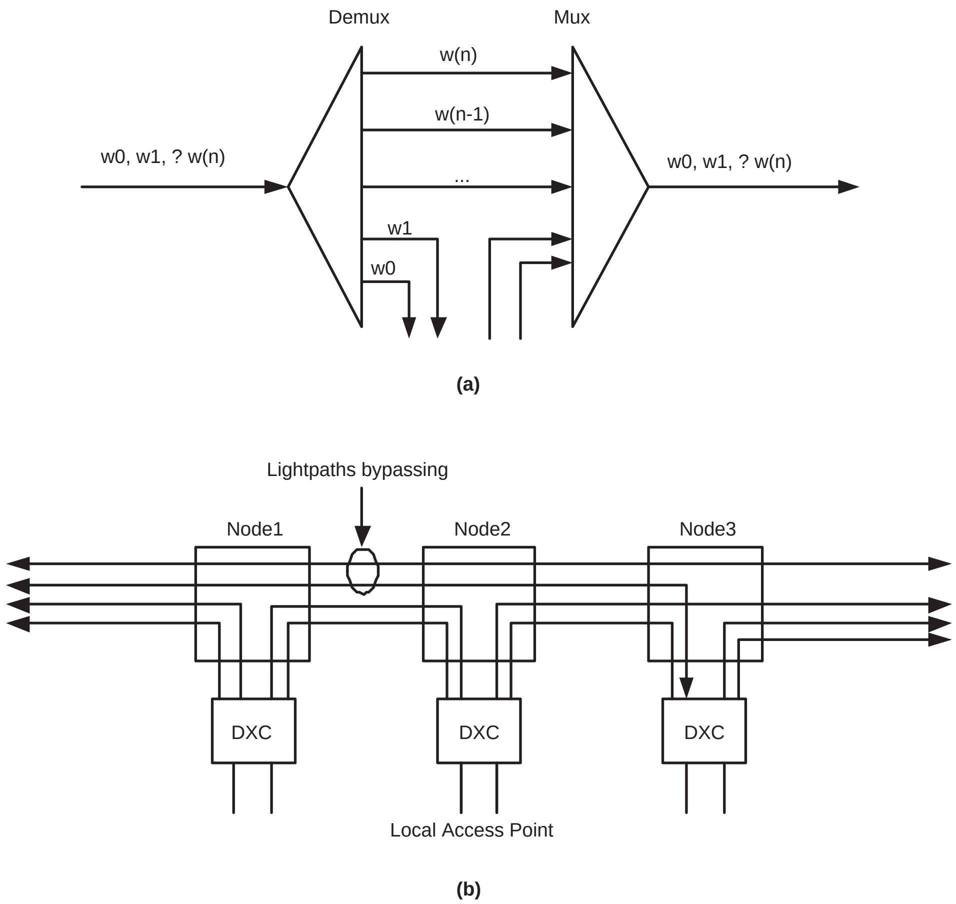


Figure 1.5: (a) OADM architecture (b) SONET ring network with hub nodes

The general traffic-grooming problem has been proven to be NP-complete

[17][18]. Many research works propose grooming problem in ring network as a network design and reconfiguration problem with the objective to minimize the number of ADMs [19][20][21]. In [19] the optimized solution is formulated as an integer linear programming problem (ILP). This is commercially feasible when the size of a network is small. However, since the computation complexity increases explosively as the network size increases, it becomes hard to use on networks of practical size. Some heuristic solutions have been studied in [18][20][22] giving greedy approaches, approximation approaches, and simulated annealing approaches to handle the problem in a large network.

Networks with nodes equipped with DXC shown in Figure 1.5(b) have been proposed in [23][24]. Multi-hop grooming is available in such networks. The study in [25] makes a comparison of network performance between single-hop grooming and multi-hop grooming (with one hub node) by simulation. The results show that when the grooming ratio is large, the multi-hop approach tends to use fewer ADMs, but when the grooming ratio is small, it is beneficial to use single-hop approach, and in general, the multi-hop approach uses more wavelengths than the single-hop approach.

Grooming in Interconnected SONET/WDM Rings

Two SONET ring networks interconnect at one or two interconnected nodes. The architecture of such a node depends on the availability of hardware. A typical node is deployed based on *optical crossconnect* (OXC). In terms of whether the actual switching is done electrically or optically, OXC can be either *opaque* or *all-optical* as illustrated in Figure 1.6. In the opaque configurations, an optical signal is converted into the electrical domain as it passes through the node. In the all-optical configuration, a signal remains in the optical domain as it passes by.

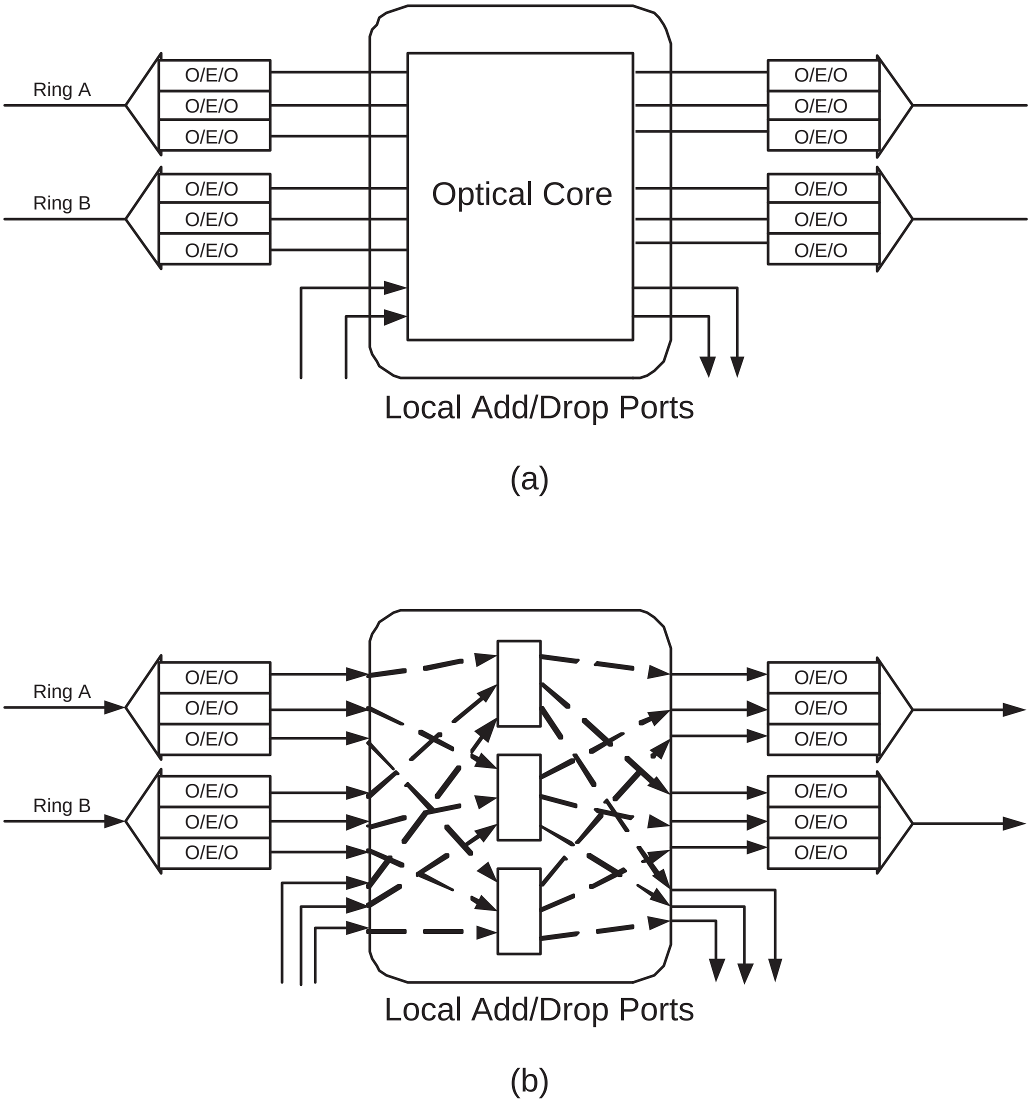


Figure 1.6: (a) Opaque optical crossconnect (b) Transparent optical crossconnect

Grooming in a single-ring network can be good reference and basis for study of traffic grooming in interconnected-ring networks. In [26], there proposes an ILP solution for traffic grooming in a network of single-point-connected double rings, and a heuristic to handle the problem on network of practice size. Its objective function is to decrease the network cost measured by the number of ADMs as most studies of single-ring networks do. When the number of rings and the number of junction nodes increase in an interconnected-ring network, the network topology tends to become an irregular mesh topology.

Grooming in Wavelength-Routed Mesh Networks

Most early research on traffic grooming focused on ring (interconnected) networks - the first generation of optical network infrastructure. The limitation of ring network makes it hard to accommodate the increasing traffic especially in a long-haul backbone network. As the optical network topologies evolve from rings to meshes, research on traffic grooming in mesh networks becomes more and more important.

Compared with ring network, mesh network is easy and efficient to configure for bandwidth provisioning and protection. And its irregular topology makes it very easy to scale. At present, a little research has focused on grooming in mesh networks. The node architecture shown in Figure 1.7 explains how traffic grooming is done in a mesh network [27].

Within the part of access station shown in Figure 1.7, there is a grooming fabric (G-Fabric) providing multiplexing, demultiplexing and switching of high-speed data streams. It can be done by the MPLS/IP router us-

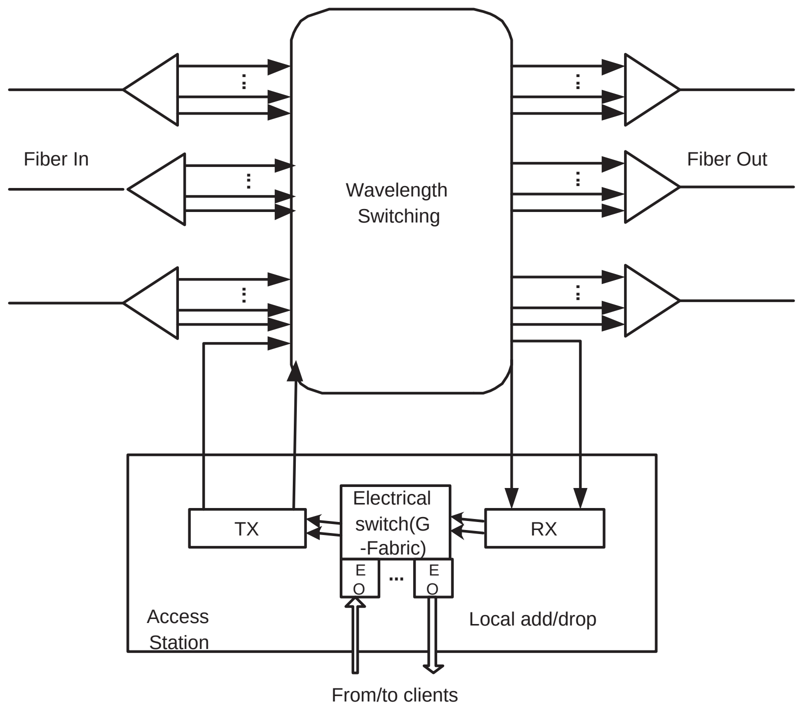


Figure 1.7: Node architecture of WXC supporting traffic grooming

ing a software-based queueing scheme. A transponder array (TX and RX) is used to connect the G-Fabric with the wavelength switching fabric (W-Fabric). The grooming capacity of the WXC is determined by the size of the transponder array. Moreover, a lightpath is called a groomable lightpath if it is switched to the G-Fabric at its end nodes.

An ILP formulation is proposed in [28] to optimize two parameters: number of wavelengths and number of transponders. Since the number of variables and equations is increased exponentially as network size increases, this formulation is unmanageable even for a small network. The authors then describe a heuristic based on *Blocking Island* (BI) [28] paradigm for practical use. This kind of problem is a strategic network-design problem.

Alternatively, in [27], by formulation, it intends to solve the operational network-design problem: for a given traffic matrix set and network resource, the formulation is either to maximize the network throughput or to minimize the connection-blocking probability. In [29], three grooming algorithms are proposed and their network performance is compared. The blocking probability, use of network resource and network throughput have been investigated as the number of receivers per port/node changes.

1.3.3 Routing on Virtual Topology

The virtual topology of a WDM network is obtained by establishing lightpaths between source and destination nodes and it is the topology that a traffic flow can make use of. Although a lot of research work has been carried out on wavelength-routed networks, traffic routing on virtual topology is rarely payed much attention to at present. In [30], the routing problem on virtual topology is regarded as the known one of routing traffic over a given topology once the virtual topology design problem, RWA and grooming problem are solved. In [31], the authors propose a dynamic multi-path routing algorithm and regard additional wavelength adding to an optical fiber as additional link in the model.

In this thesis, routing on virtual topology will be the main focus. Particularly, traffic grooming will be taken into account for such routing. In addition, some traffic characteristic such as traffic lifetime will be considered in making routing and grooming decision.

1.4 Contributions of the Thesis

The contributions elaborated throughout the thesis are outlined as follows [32].

- A traffic routing heuristic algorithm called MURT is presented. This algorithm deals with the problem of making routing decision in case that multiple lightpaths exist between two nodes. Particularly, the algorithm considers traffic grooming in making routing decision. The proposed grooming policy intends to groom traffic flows onto the lightpath with most-used wavelength. Simulation results and evaluation of the algorithm are carried out, which show that MURT can improve network performance as compared with OSPF algorithm without considering traffic grooming in routing.

- Taking into account the effect that long-lived flows bring to network performance, MURT algorithm is extended to an algorithm called MURT-LL. With MURT-LL, this effect is examined when a long-lived flow is detected and corresponding actions are taken by the routing algorithm. Simulation results show that the extended MURT-LL algorithm can further improve network performance.

1.5 Structure of the Thesis

The remaining of this thesis is organized as follows: *Chapter 2* investigates the special situations for routing in virtual topology and introduces the MURT algorithm. Some simulation results, which show the performance improvement by adopting MURT, are also presented. *Chapter 3* introduces some features of long-lived flows and proposes an extension of MURT, called MURT-LL, to handle long-lived traffic. Supplemental simulation is done as well. Finally, *Chapter 4* concludes the thesis and discusses some issues for possible further research.

Chapter 2

Routing Based on Grooming

2.1 Introduction

Till now, traffic routing over a physical topology has been extensively studied with many algorithms existing. In addition, routing on virtual topology has been thought to be the same as on physical topology if the RWA and the grooming issues are solved [30]. However, compared with physical topology, virtual topology introduces some special network situations. As logical links in a virtual topology, new lightpaths can be established when existing virtual topology cannot accommodate new connection requests and disconnected while no traffic is on within a timeout period. As a result, current route selection can affect the lifetime of a lightpath and consequently the virtual topology, leading to interfering with service for future connection requests. Hence, routing in such a network needs to consider the transformation of the virtual topology after a routing decision, and the effect which the new virtual topology has on acceptance of future requests. While traditional routing algorithms such as the Open Shortest Path First (OSPF) on physical topology do not pay attention to effect of special situations brought by virtual topology, we are interested in this and as well the relationship between traffic routing and grooming policy.

In this chapter, we propose a scheme of traffic routing considering grooming policy. In this scheme, the usage of wavelength is regarded as an important criterion for making grooming and routing decision, since wavelength is quite lacking compared with the huge bandwidth capacity in a WDM network. With this scheme, in case that multiple lightpaths exist between a pair of source and destination nodes on the virtual topology, one lightpath is chosen by taking into account the resulting change of the virtual topology.

2.2 Routing Based on Grooming Policy

2.2.1 Problem Description and Network Model

We consider an IP-over-WDM network, in which, each node contains a *wavelength crossconnect* (WXC) to support traffic grooming. A simplified architecture of such a node is discussed in Chapter 1 and illustrated in Figure 1.7. We assume that each node has unlimited multiplexing/demultiplexing capability and can multiplex as many as possible low-speed traffic flows to a lightpath as needed, as long as the lightpath can accommodate the aggregated traffic. Besides, wavelength conversion is not used.

In this chapter, we assume the network traffic is dynamic, i.e. connection requests come and depart in a random manner. When a connection request is originated at a source node, it can be groomed to an existing lightpath. If no groomable lightpath is available, a new lightpath has to be established on the physical topology. If there are more than one groomable lightpaths between the source and destination of the request, a routing decision is made to choose one lightpath from these multiple groomable lightpaths considering grooming policy. A lightpath is released when no traffic is on it within a timeout period.

2.2.2 Routing Based on Grooming Policy

Since a virtual topology is composed of lightpaths - serials of physical fiber links and nodes, it introduces some special features for a routing algorithm to consider. It is impractical to establish lightpaths between every pair of nodes as discussed in the previous chapter. Besides, in a virtual topology as seen by the traffic routing algorithms, a lightpath is regarded as a logical link between its end nodes. Since a lightpath is established and released relating to connection requests, the number of logical links vary between two nodes. As a result, a logical link is established or released relating to the connection requests and the number of logical links between two nodes can change from zero to multiple.

As for a routing algorithm, it is affected by the situations of virtual topology. The logical links (ligntpath) are circuit connections in nature and network resource such as wavelength is occupied when a logical link is set up. Path chosen by the routing algorithm decides what resource is occupied or released, which in turn affects the accommodation of future connection requests. Moreover, establishment of a logical link (ligntpath) is a time-consuming process compared with packet switching. Therefore, frequent establishment or release is not preferred. Another problem is that while many existing routing algorithms can provide suggestion of path selection for packet switching hop by hop, seldom gives advice on link selection in case of multiple links between two nodes.

To solve the above problems, routing decision can be made in combination with wavelength usage constrained by grooming policy. Wavelength of a fiber link is a very important resource in a WDM optical network. As a result, different solutions in grooming policy for making use of wavelength have different impact on network performance.

Figure 2.1 shows two solutions to use wavelength. In this figure, Figure 2.1.(a) is the virtual topology of some physical network composed of 4 OXC (optical crossconnect) nodes and links each containing 2 wavelengths, $w0$ and $w1$. In addition, three lightpaths, $lp1$ using $w0$, $lp2$ using $w0$ and $lp3$ using $w1$, are existing on this network. Three requests $r1(3, 1, *)$, $r2(1, 2, *)$ and $r3(0, 2, *)$ are coming sequentially, where in the triple (s, d, b), s represents the source, d the destination and b the required bandwidth. $r1$ can be groomed on $lp1$ and $r2$ can be groomed on either $lp2$ or $lp3$ if enough free bandwith on the lightpath is available. If $lp3$ is chosen for $r2$ and $w1$ is occupied, before the traffic of $r1$ or $r2$ finishes and resource on $lp1$ or $lp3$ is released, it is not possible to setup a lightpath between $\langle 0, 2\rangle$ for $r3$ without wavelength

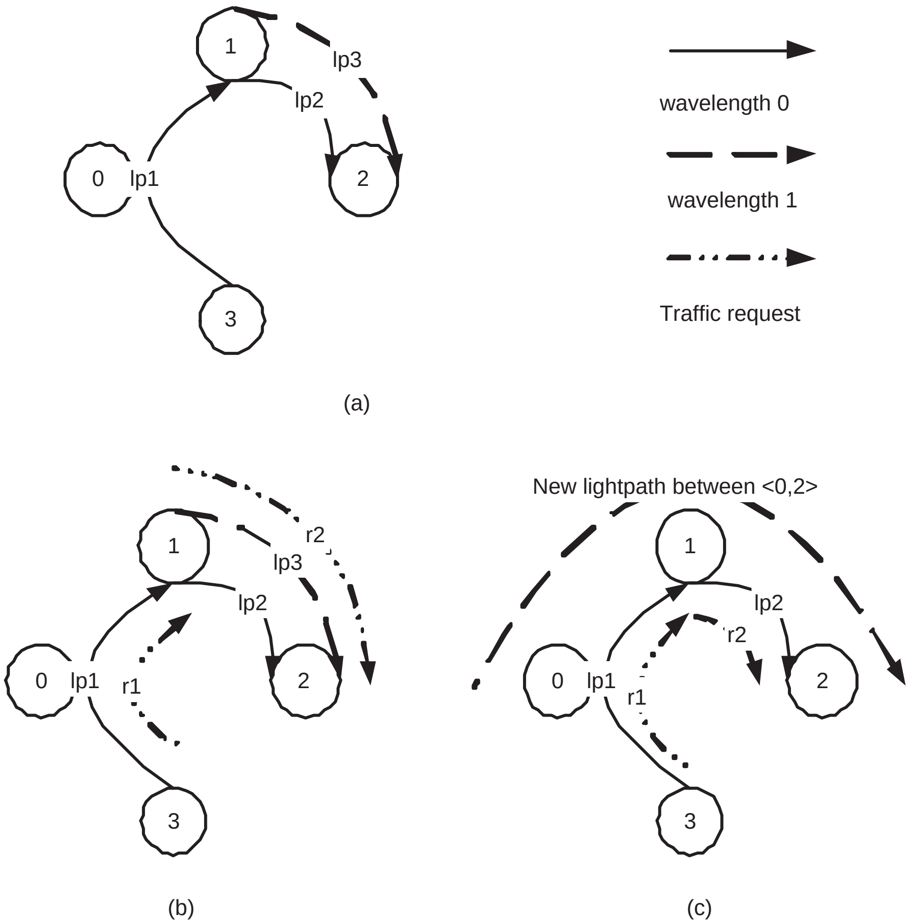


Figure 2.1: Illustrative Example of Grooming Policy to Make Use of Wavelength for WDM Mesh Networks (a) Virtual topology of three lightpath $lp1$, $lp2$ and $lp3$. (b) If $lp3$ is assigned for $r2$, before $r1$ or $r2$ finishes transmission and the lightpath is released, no resource is available to setup a lightpath connecting $\langle 0, 2\rangle$ for $r3$. (c) If $lp2$ is assigned for $r2$, after existing traffic leaves $lp3$ and $lp3$ is torn down, new lightpath of $\langle 0, 2\rangle$ can be setup for $r3$

conversion (illustrated in Figure 2.1.(b)), where $\langle s, d\rangle$ denotes a light path starting at s and ending at d. But if $lp2$ is selected for $r2$, after existing traffic on $lp3$ is transmitted over and resource is released, new lightpath connecting $\langle 0, 2\rangle$ can be setup successfully and $r3$ will not be blocked (illustrated in Figure 2.1.(c)). This example shows that if we can increase the utilization of used wavelengths, say, grooming on lightpath of $w0$ in this case, other wavelengths ($w1$) can be "saved" for future use for new connection requests.

In a WDM mesh network where transponders are enough and wavelength is relatively scarce, wavelength occupancy (WO) can be a constraint for grooming policies apart from hop count and other resource utilizations [27]. Here, the wavelength occupancy of w_i is defined to be the ratio of the number of lightpaths using w_i and the total number of lightpaths. From Figure 2.1 and its discussion above, we have seen an example of how wavelength occupancy can affect grooming in WDM mesh networks. In this example, the idea is similar to the Most-Used wavelength assignment algorithm mentioned in [33] for RWA on the physical topology.

In physical topology, optimal use of wavelength is preferable and can produce good performance in terms of connection-blocking probability. This has been demonstrated by many wavelength assignment (WA) algorithms which include: random-fit (RF), first-fit (FF), least-used (LU), most-used (MU), min-product (MP), least-loaded (LL), max-sum (MS) and relative capacity loss (RCL) [34].

In the following, we propose to extend the idea of optimizing wavelength usage to grooming policy. For this, we define the utilization of a wavelength in a network as the ratio of the sum of occupied wavelengths on each fiber link and the sum of total number of wavelengths on each fiber link. When a set of multiple groomable lightpaths exist between one pair of nodes, the proposed grooming policy sorts these lightpaths by the order of wavelength occupancy of each wavelength occupied by lightpaths in the set, i.e. most-used order.

This most-used policy means to compress the usage of lightpaths by packing the usage of wavelengths and conserve the spare capacity of lightpaths with less-used wavelengths.

Since grooming policy affects path selection, routing decision can be made as a result of combined consideration of both traffic routing algorithm and grooming policy on the virtual topology in WDM mesh networks. In virtual topology, the routing algorithm can choose a logical link from multiple logical links between a node pair based on the grooming policy. When the number of wavelength on each fiber link is the main constraint on physical topology, grooming policy selects a lightpath adapting to wavelength occupancy. As a result, routing decision is affected by wavelength occupancy as well. In particular, the following is the description of the proposed heuristic grooming policy and the corresponding routing scheme.

Grooming policy heuristic:

1. When a connection request comes, find on the virtual topology the set of existing lightpaths with the same source and destination pair as the request.

2. Sort this set of lightpaths by the non-increasing order of utilization of each wavelength over the network, i.e. most-used first.

3. Select the first lightpath with enough spare capacity from the lightpath set sorted in Step 2 and groom traffic to this lightpath.

4. If this grooming policy cannot decide a unique lightpath for the request, use OSPF to select a groomable lightpath.

For traffic routing, OSPF is used for information broadcasting and the result of the grooming policy is referred for path selection. The routing algorithm works as follows:

1. When a connection request arrives, try to select a lightpath for the request using the grooming policy described above.
2. If existing lightpaths cannot accommodate this connection request, RWA is applied to establish a new lightpath on the physical topology according to the bandwidth requirement of the request.
3. If the setup fails, block this request; otherwise, go to the next step.
4. Switch and possibly groom traffic sessions on the selected lightpath and begin data transfer.
5. A lightpath is torn down when no traffic is on within a timeout period.

2.3 Simulation Study

2.3.1 Simulation Scenario

The performance of the proposed scheme, which is routing with regard to most-used grooming policy (MURT), is evaluated by simulation. In the simulated network, the MURT scheme is applied at each node. A comparison is made between the proposed MURT scheme and OSPF routing without considering grooming. As shown in Figure 2.2 and Figure 2.3, the two simulated physical wavelength-routed networks, Network 1 and Network 2, are composed of 10 nodes and 16 nodes respectively, and their topologies and arcs are generated randomly. Between each pair of adjacent nodes, there is one bi-directional link of capacity of 30 bandwidth units on both networks. The number of wavelengths in each link of the two networks is 12.

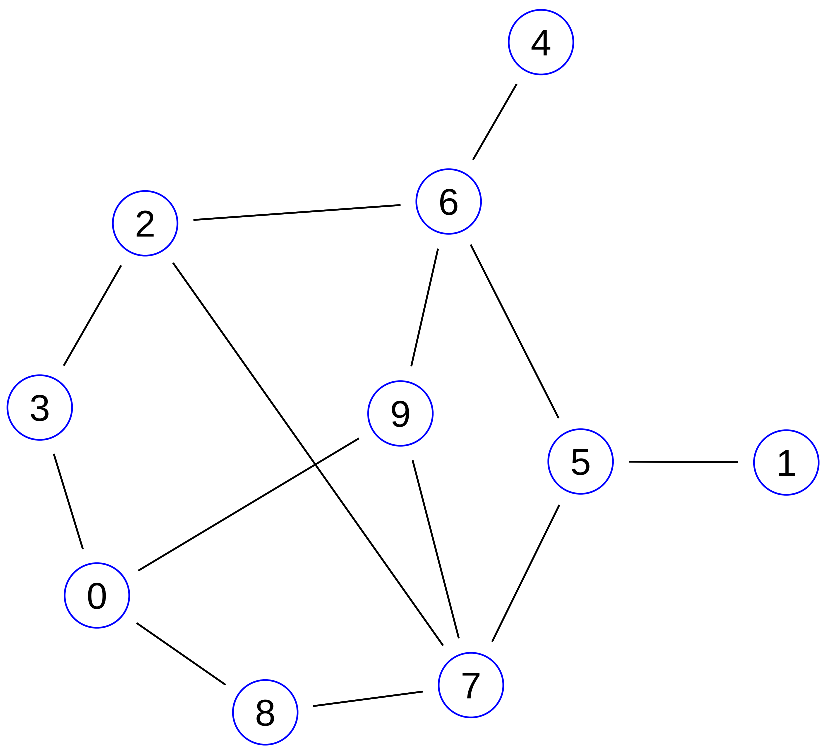


Figure 2.2: Example Network 1: Network of 10 Nodes

We assume in the simulation that the $\langle source, destination \rangle$ pairs of demands are chosen randomly. The traffic flows obey an on-off traffic model in the system which are modelled by a Poisson arrival with mean session arrival rate λ and the holding time of each session has an exponential distribution with mean traffic session service/holding time μ^{-1}. In addition, the packet

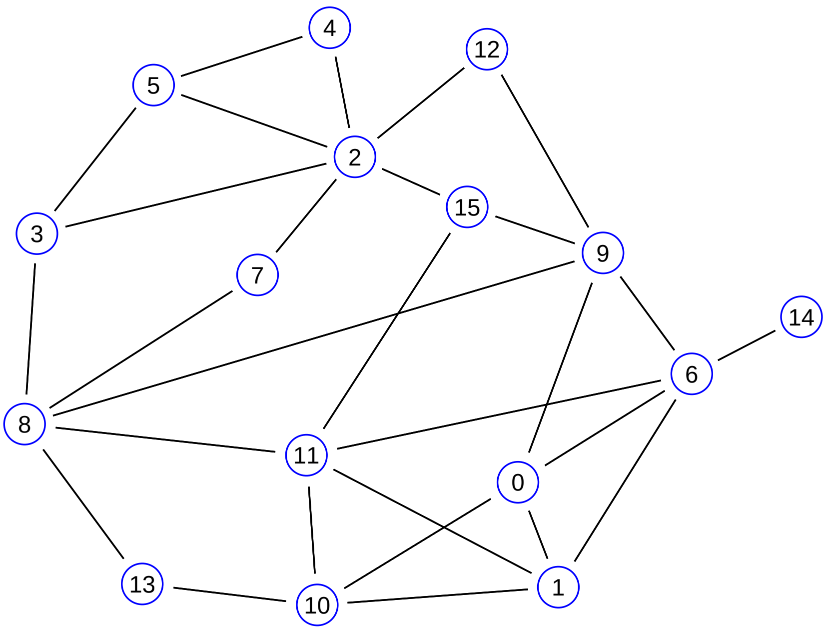


Figure 2.3: Example Network 2: Network of 16 Nodes

arrival in each traffic session is also exponentially distributed. Some other assumptions are as follows:

- The routing algorithm implemented for RWA on the physical network is Exhausted Routing algorithm (least-congested-path [35])
- Random-fit wavelength assignment algorithm is used for RWA on the physical network [34].

We set up our simulation using Network Simulator 2 with the help of a third-party package: OWNS [36] for a wavelength-routed platform.

2.3.2 Result Analysis

Figures 2.4 - 2.9 compare the performance of MURT and traffic routing without considering the effect of grooming policy (OSPF). In Figures 2.4 and 2.5, it can be observed that when traffic load is low, blocking probabilities of these two schemes are similar because generally only one lightpath (logical link) is needed between each pair of nodes. In this case, optimizing the usage of wavelength shows little effect. However, as traffic load increases, MURT performs better than OSPF. This is reasonable because MURT selects lightpaths with most-used wavelength for grooming, leading to grooming traffic flows into fewer lightpaths. As a result, more lightpaths with less-used wavelengths can be released more quickly and these wavelengths are then free to be used to establish new lightpaths on the physical topology. In addition, since MURT conserves the spare capacity of lightpaths with less-used wavelengths, more traffic flows may be groomed into existing lightpaths instead of establishing new lightpaths.

Figure 2.6 and Figure 2.7 illustrate the relationship between each session traffic load and average wavelength utilization defined as the number of busy wavelengths over the number of all wavelengths. Figure 2.8 and Figure 2.9 are the link utilization property. The results show that scheme MURT has higher average wavelength utilization and link utilization. That is to say, under the same network conditions and traffic scenario, scheme MURT uses more wavelengths and links than the other scheme. As traffic load becomes heavier, the difference remains noticeable. This indicates that the proposed scheme can provide better performance on wavelength utilization and link

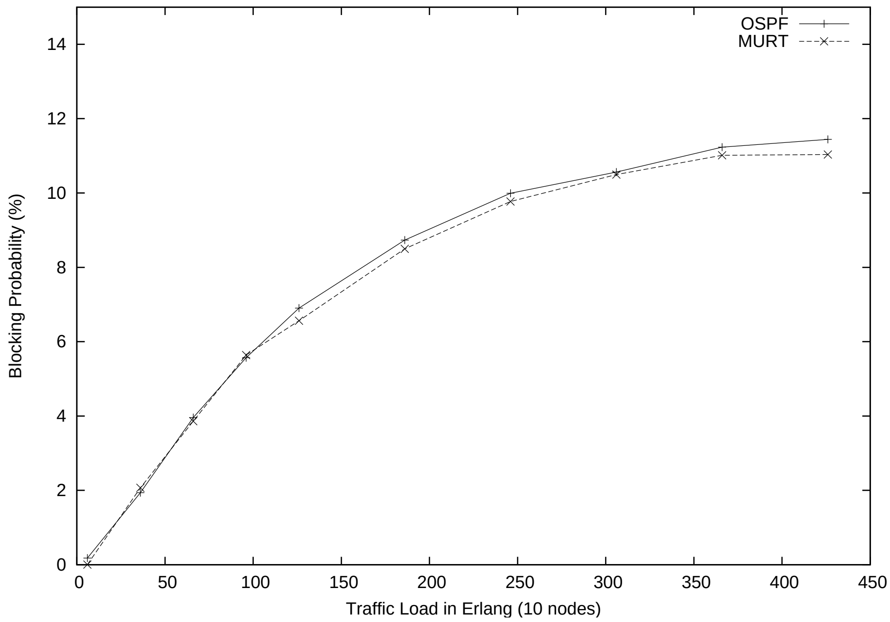


Figure 2.4: Blocking probability for Network 1

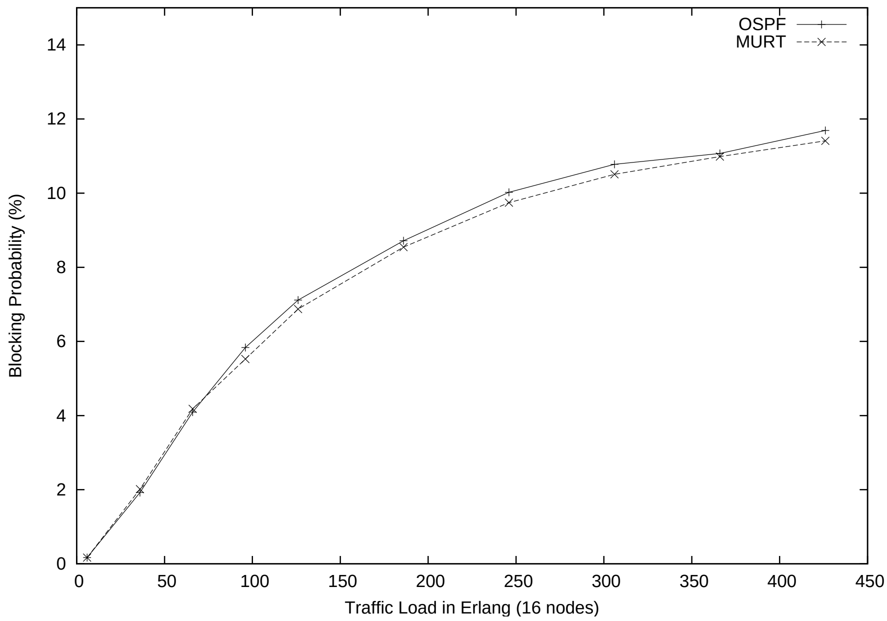


Figure 2.5: Blocking probability for Network 2

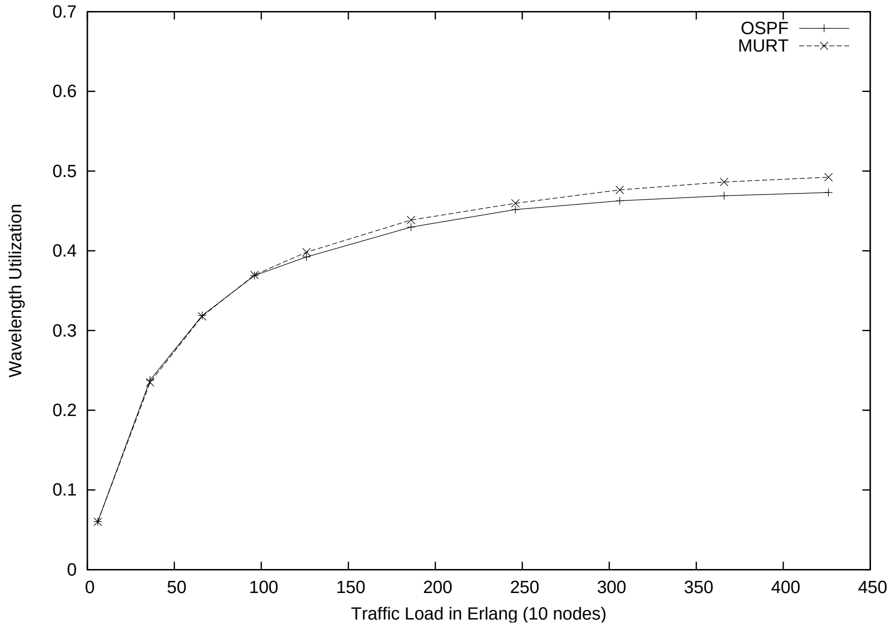


Figure 2.6: Wavelength Utilization for Network 1

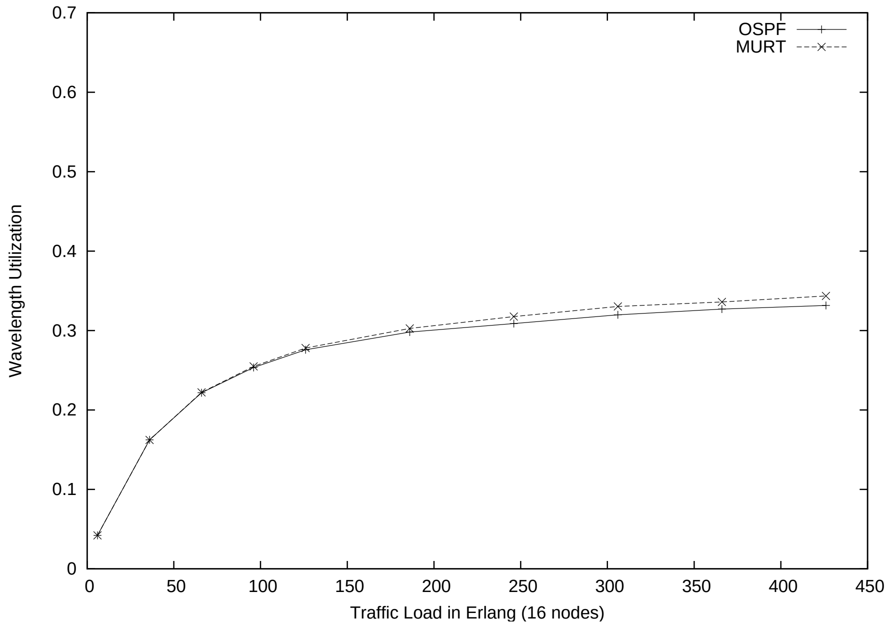


Figure 2.7: Wavelength Utilization for Network 2

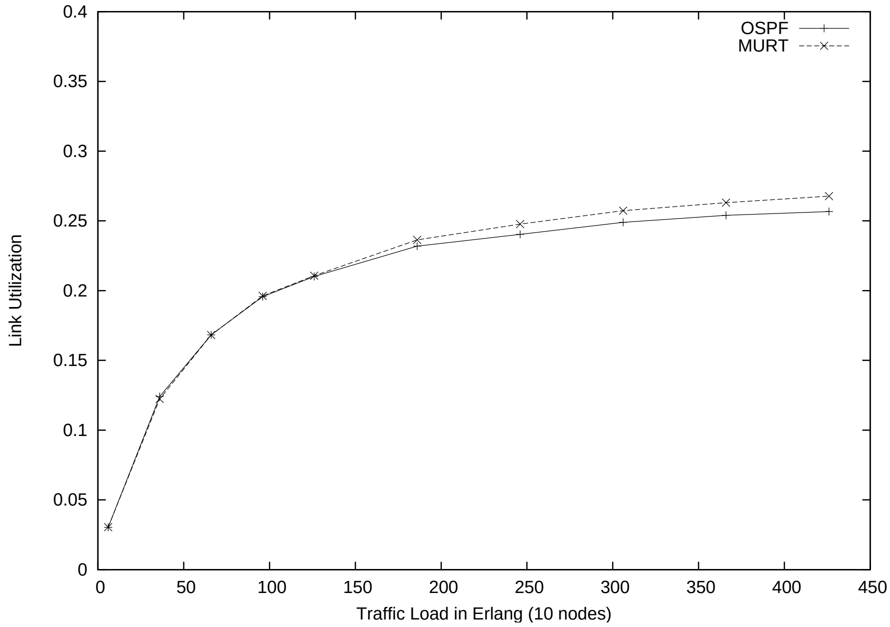


Figure 2.8: Link Utilization for Network 1

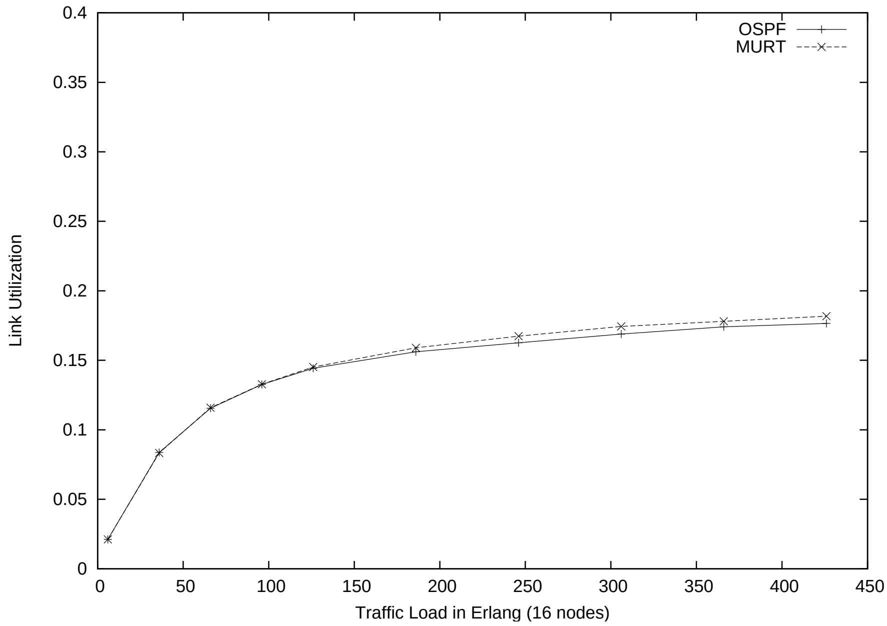


Figure 2.9: Link Utilization for Network 2

utilization when traffic load is high. This is understandable as a result of lower blocking probability. Since under the same condition, less connection requests are refused, more are accepted and use more wavelength and link bandwidth with the MURT grooming-combined routing algorithm.

2.4 Summary

In this chapter, we present a routing algorithm considering grooming policy on virtual topology for wavelength-routed networks. In this routing algorithm, we take into account the effect that a grooming policy has on virtual topology, and how present path selection interferes with future connection requests. We evaluate the proposed algorithm by comparting it with a routing scheme that does not take grooming policies into account. Simulation results show that the proposed algorithm can help to make choice from multiple links. Furthermore, compared with just treating routing and grooming as unrelated matters, it reduces blocking probability and enhance bandwidth utilization of the network.

Chapter 3

Optimization for Long-Lived Traffic

3.1 Introduction

A traffic flow (or in short a flow) is defined as a bi-directional traffic stream. It is partitioned based on various temporal and spatial conditions, i.e. a flow specification and a timeout period, as observed at edge points in a network. A flow is active if the following requirements are met.

- Its packets meet the flow specification. For example, a flow may consist of all packets routing between the same $\langle source, destination \rangle$ pair, or,between the same AS pair, or, CIDR block. The aggregate granularity can be dynamic as the result of the tradeoff between the number of flow states that are needed for flow classification in the network and the levels of service difference between traffic groups. In general, the coarser the granularity is, the less service levels are applied to different traffic.

- The arrival interval between packets is less than a specified timeout value.

In Figure 3.1, a timeout-based flow model is illustrated. The upper part of the figure shows how timeout can separate observed packets to flows. The lower part of the figure gives an example of multiple independent flows that are active simultaneously. This flow model got in-depth study in [37].

Flows can be classified as short-lived and long-lived. A flow is a long-lived one if the number of packets arriving on the flow reaches a threshold packet count, or the length of time that a flow is active triggers a timer to timeout. Otherwise, it is considered to be short-lived [37].

A lot of studies give mathematical analyses or heuristics to prove that establishing dedicated connections (shortcuts) for long-lived flows can improve network performance [38] [39] [40] [41] [42] [43]. This is obtained by reducing packet forwarding cost on the intermediate routers and making use of quality-of-service features in the switching hardware. In addition, establishing shortcuts to long-lived flows can help to balance network load by directing the shortcuts to underutilized links. Research on traffic characteristics shows that the 'long-lived' flows just occupy a very small ratio of all the traffic flows in Internet, while they account for a high proportion of packets (bytes) on a link [37] [44] [45]. Especially in a scenario described in [45], about 1.5% of the observed streams were long-running / long-lived

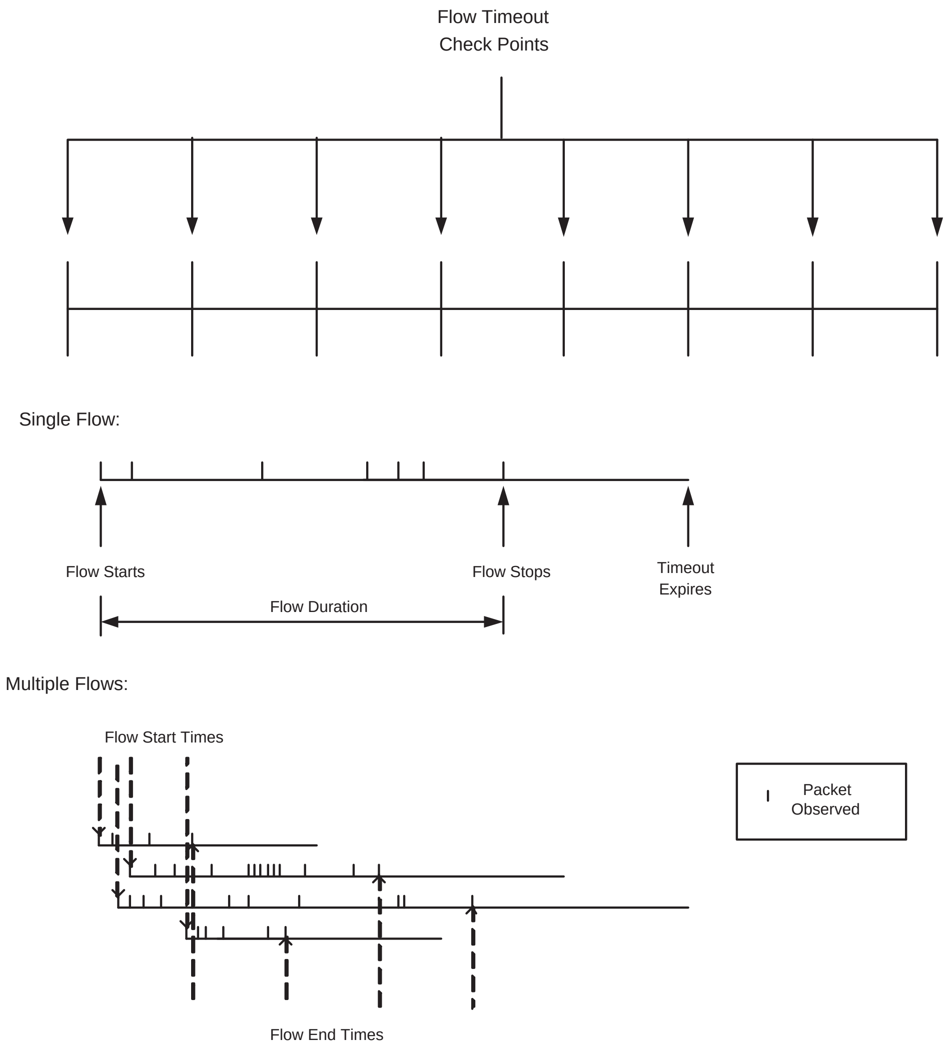


Figure 3.1: Timeout-Based Flow Model

and 70% of the streams were very-short / short-lived, while up to 50% of all bytes were in the long-running streams. The results in [44] exhibit that optimizing just the longest 5% of the flows can benefit more than 30% of all the packets. And this trend still exists after several levels of aggregation [38]. Viewing these, we propose to conduct grooming and routing considering by taking into account this traffic characteristic. Since distinguishing traffic by its duration is relatively simple and easy to operate, without carrying much control information and complex computation, this characteristic of traffic flows can be used to improve network performance especially when traffic load is heavy.

Extending the research introduced in the previous chapter, optimization for long-lived traffic is considered in this chapter.

3.2 Optimization for Long-Lived Traffic

3.2.1 Problem Description

When a long-lived connection is groomed to a lightpath, this lightpath is active for at least a time as long as the lifetime of this long-lived connection. The active duration maybe even longer if new connection requests arrive before the transmission of the long-lived one is finished. This is shown in Figure 3.1.

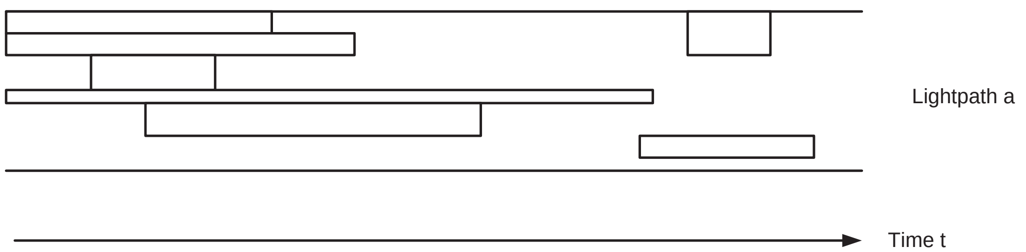


Figure 3.2: Active Lightpath. A lightpath is kept active after transmission of a long-lived lightpath if new request arrives before the end of transmission of the long-lived one.

A lightpath is active if either connection on it is under transmission.

Hence, there is much larger probability for a new arriving connection request to choose this lightpath than to require to establish a new one. As discussed in the previous chapter, it is beneficial for network performance if traffic requests choose to groom to the lightpath occupying the wavelength with largest wavelength occupancy (WO) among all available lightpaths. Moreover, a lighitpath with smaller wavelength occupancy should be released as soon as possible.

When a long-lived traffic request activates a lighitpath for a long time, the resource occupied by the lightipath is hold for a long time as well, no matter whether the situation obeys the optimization grooming policy mentioned in Chapter 2. Then there is a possibility that during the processing of long-lived connection transmission, the network status has changed and the lightpath with this connection is no more the one with the largest wavelength occupancy among its parallel lightpaths. In addition, since this lighitpath is active for a long time, there is more change for it to be active longer than lightpaths without a long-lived connection. As a result, there are more chances that less optimized resource is occupied longer. This situation can be illustrated by Figure 3.2.

In Figure 3.2.(a), a lightpath is established for a group of groomed traffic flows. Since there is a long-lived flow, new arriving flows can also use this lightpath if they come before the end of the long-lived flow and there is enough bandwidth. Although there is a possibility that this lightpath is not an optimized one for the traffic between the source and destination nodes, the long-lived flow helps to activate the lightpath for a long period. As shown

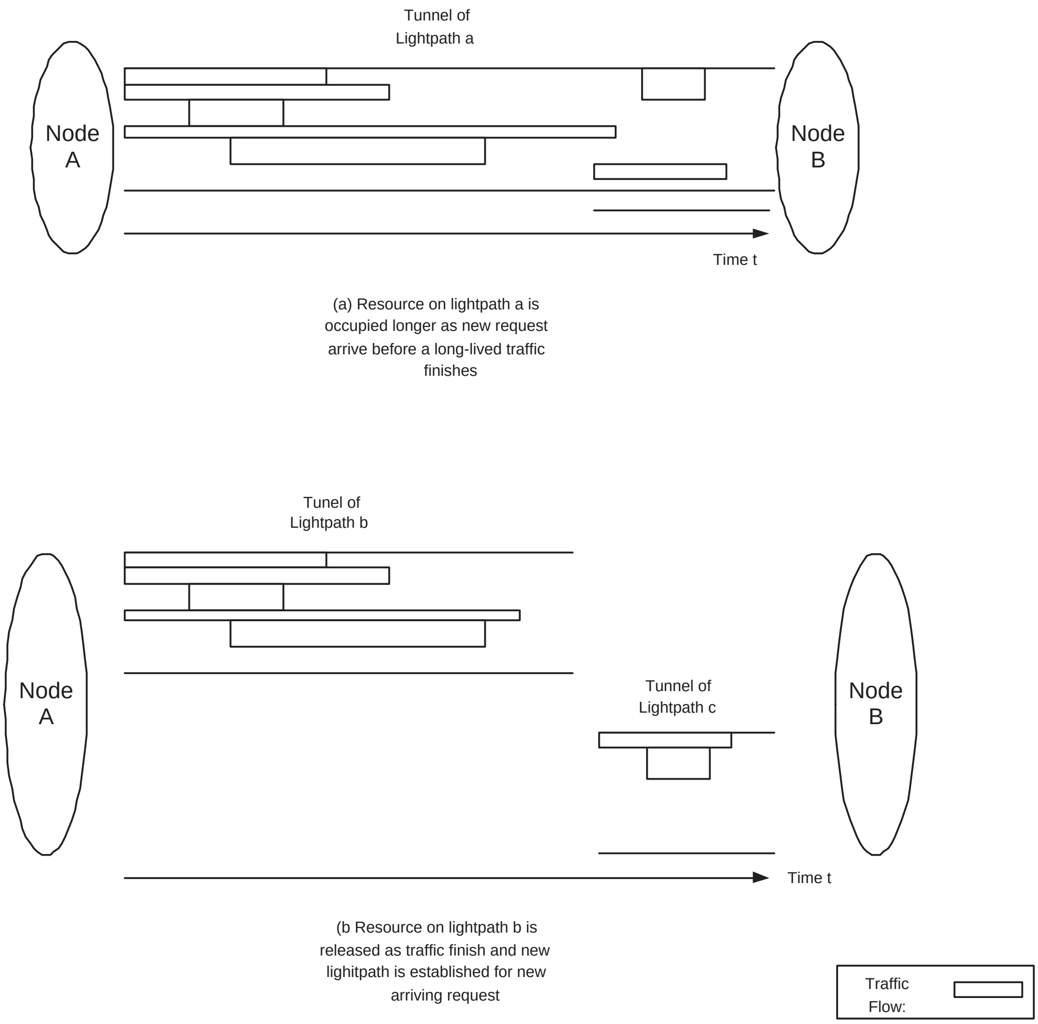


Figure 3.3: Active Lightpath. A lightpath is still active after transmission of a long-lived lightpath if a new request arrives before the transmission of the long-lived one.

in Figure 3.2.(b), there is no long-lived flow but short-lived ones. In case that lightpath b is not optimized for transmission between node A and B, it can be release some time after the transmission of the last flow is finished, and a new lightpath c is established for new flows, which can optimize resource usage for the new arriving flows.

The key point of this problem is that, a long-live traffic flow can affect the network performance greatly. If the effect is positive, it should be protected and last. On the other hand, if the effect is negative, it should be ameliorated as much as possible.

3.2.2 Separating Short-Lived and Long-Lived Traffic

Although traffic flows are aggregated (or groomed) in the network model through WXC, the property that the majority of packets belong to long-lived flows still persists. In a wavelength-routed network, an aggregated flow on a lightpath can be identified as long-lived or short-lived by its lifetime. In WXC at each node of the network, a timer is implemented as a flow meter to classify flows into short-lived and long-lived ones. When a flow is originated at a source node, a timer is initiated for it. Once a timer counts a timeout value, the flow is marked as a long-lived one. Another way is to set a byte or packet counter, to keep track of the number of bytes or packets that have arrived on each flow. When the accumulated size of the flow has exceeded some threshold, the flow is classified as a long-lived one [38].

3.2.3 Solution for Optimization

In the previous chapter, a grooming policy and a routing algorithm are proposed. In this chapter, they are extended to consider traffic lifetime. The main idea of algorithms introduced in the previous chapter is to optimize the use of resource such as wavelength on each fiber link. Since long-lived traffic flows contribute a large ratio of packets, and they occupy lightpaths for a long time compared with short-lived flows, the use of resource for long-lived flows can affect network performance much more. Therefore, optimizing resource usage for long-lived traffic is significant.

For the grooming policy, the aim is to aggregate flows to a lightpath with the most-used wavelength. If no other lightpath occupied a wavelength of smaller wavelength occupancy (WO) than one lightpath did, this lightpath is called optimized. Since a lightpath has a very broad bandwidth compared with single traffic flow, it is assumed in our research that a flow would not be split to run on multiple lightipaths. As the link state of networks varies from time to time, an optimized lightpath for a flow always becomes not optimized after operation for some time. This situation is even more notable for flows of long lifetime, which brings influence on network performance. In our research, this problem is solved by checking whether the lightpath is still optimized for a flow once it is flagged as a long-lived flow. If the lighipath is not optimized, i.e. another lightpath with more-used wavelength exists or a new lightpath with more-used wavelength could be established on the physical topology, the lightpath is locked so that no new flow can be groomed into this lighpath. In this way, this lightpath could be released as soon as the transmission is over and resource on the lightpath can be set free as soon as possible. In particular, the following is the description of the proposed heuristic grooming policy and routing scheme.

Grooming policy heuristic:

1. Groom a traffic flow to a lightpath (if available) by the grooming policy

defined in Chapter 2.

2. Startup a packet counter for each traffic flow to track accumulated number of packets of this flow.

3. If a counter triggers to detect a long-lived flow, check whether this flow was occupying the optimized resource as described in Step 4 and Step 5. If the result is positive, no additional action is done, otherwise, go to Step 6.

4. Let WO_i represent wavelength occupancy of each wavelength i occupied by a set of lightpaths between the same source and destination nodes, and n is the total number of lightpath in this set. Let WO_{long} represent the WO of the wavelength occupied by the lightpath on which a long-lived traffic transmits. For any WO_i where $0 \leq i < n$, if there exists an i satisfying $WO_i > WO_{long}$, then the lightpath on which this long-lived traffic flow transmits is regarded as not optimized for the long-lived flow.

5. Test whether a new lightpath with a wavelength of WO_i, where $WO_i > WO_{long}$, can be established directly on the physical topology. If the result is true, the resource for this long-lived flow is also thought as not optimized.

6. Lock the lightpath bearing the long-live traffic. Thus, no new connection request can use this lightpath unless no other resource is available for the new request.

For traffic routing, OSPF is used for information broadcasting and the result of the grooming policy is referred for path selection. The routing algorithm works as follows:

1. When a connection request arrives, try to select a lightpath for the traffic using the grooming policy described above.
2. If existing lightpaths cannot accommodate this connection request, RWA is applied to establish a new lightpath on the physical topology according to the bandwidth requirement of the request.
3. If the setup fails, refuse this request; otherwise, go to the next step.
4. Switch and possibly groom traffic on the selected lightpath and begin data transfer.
5. A lightpath is torn down when no traffic is on within a timeout period.

3.3 Simulation Study

3.3.1 Simulation Scenario

The performance of the proposed scheme, which is an extending version of the routing algorithm - MURT described in Chapter 2, is evaluated by simulation. The name is abbreviated as MURT-LL in this chapter. In the simulated network, the MURT-LL scheme is applied at each node. A comparison is made between the proposed MURT-LL scheme and the MURT scheme discussed in Chapter 2. The simulation settings are similar to what have been used for investigating the performance of MURT in Chapter 2. Particularly, as shown in Figure 3.4 and Figure 3.5, the two simulated physical wavelength-routed networks, Network 1 and Network 2, are composed of 10 nodes and 16 nodes respectively, and their topologies and arcs are generated randomly. Between each pair of adjacent nodes, there is one bi-directional link of capacity of 30 bandwidth units on both networks. The number of wavelengths in each link of the two networks is 12.

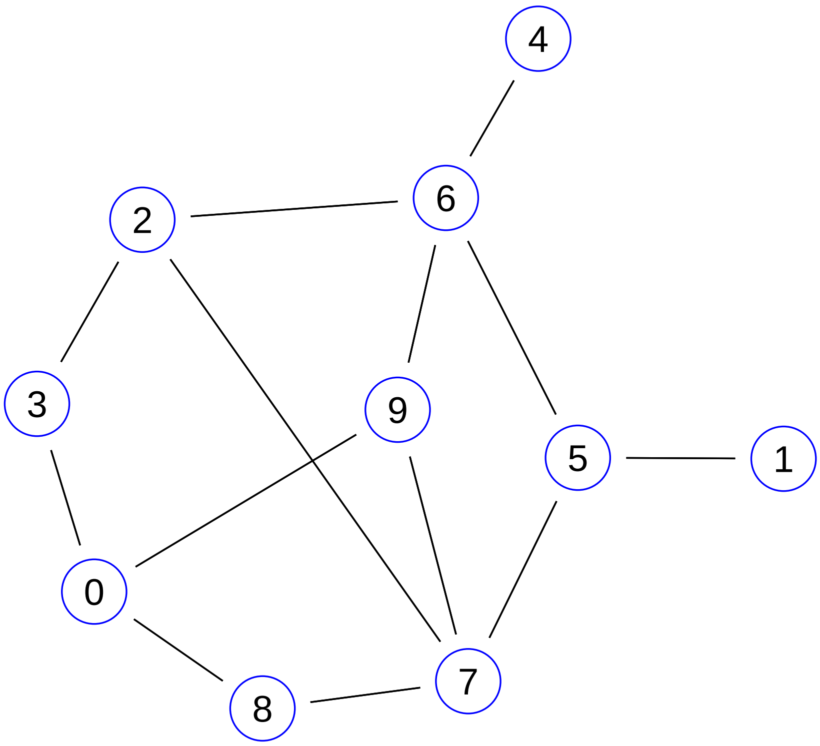


Figure 3.4: Example Network 1: Network of 10 Nodes

We assume in the simulation that the $\langle source, destination \rangle$ pairs of demands are chosen randomly. The traffic flows obey an on-off traffic model in the system which are modelled by a Poisson arrival with mean session arrival

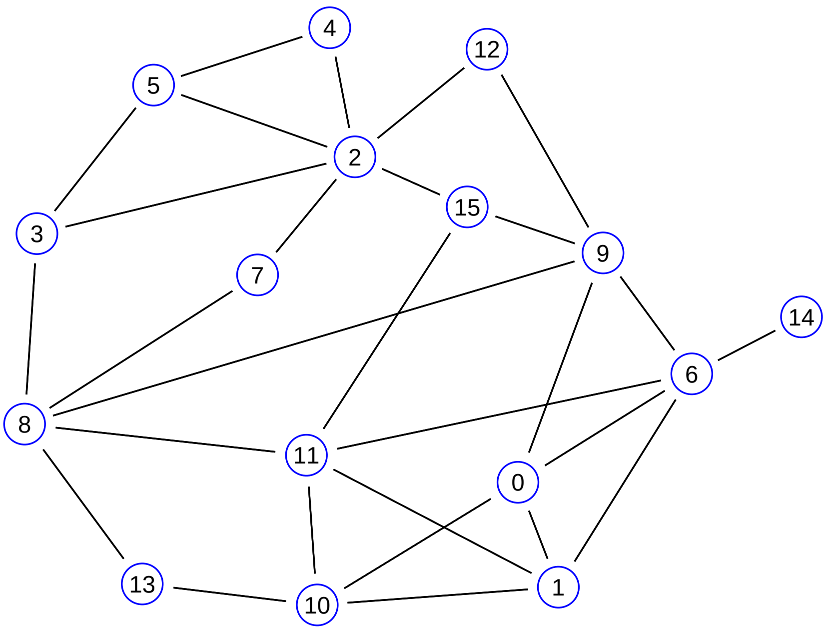


Figure 3.5: Example Network 2: Network of 16 Nodes

rate λ and the holding time of each session has an exponential distribution with mean traffic session service/holding time μ^{-1}. In addition, the packet arrival in each traffic session is also exponentially distributed. Some other assumptions are as follows:

- The routing algorithm implemented for RWA on the physical network is Exhausted Routing algorithm (least-congested-path [35])
- Random-fit wavelength assignment algorithm is used for RWA on the physical network [34].

We set up our simulation using Network Simulator 2 with the help of a third-party package: OWNS [36] for a wavelength-routed platform.

3.3.2 Result Analysis

Figures 3.6 - 3.11 compare the performance of MURT-LL with MURT. In Figure 3.6 and 3.7, it can be observed that when traffic load is low, blocking probability of the two schemes are similar because generally only one lightpath (logical link) is needed between each node pair. In this case, optimizing resource usage for long-lived traffic shows little effect. However, as traffic load increases, MURT-LL performs better than MURT, which coincides with our discussion. Because in MURT-LL, when a long-lived traffic flow is detected, the effect of resource usage for a long-lived traffic flow is evaluated. If the effect is thought to be inadequate for network performance, the MURT-LL scheme helps to release the corresponding resource as soon as possible without affecting accommodation of new arriving connection requests. As a result, optimized resource usage can be protected and maintained and dissatisfactory usage can be ameliorated as much as possible. By simulation, this policy is proved to be beneficial to decrease blocking probability.

Figure 3.8 and Figure 3.9 illustrate the relationship between each session traffic load and average wavelength utilization defined as the number of busy wavelengths over the number of all wavelengths. Figure 3.10 and Figure 3.11 are the link utilization property. The results show that scheme MURT-LL has higher average wavelength utilization and link utilization. This is to say, under the same network conditions and traffic scenario, MURT-LL uses more wavelengths and links than the other scheme. As traffic load becomes heavier, the difference remains noticeable. These figures indicate that MURT-LL can provide good performance on wavelength utilization and link utilization when traffic load is high. This is understandable as a result of lower blocking probability. Since under the same conditions, with MURT-LL, less connection requests are refused, more are accepted and more wavelength and link bandwidth are occupied.

Figures 3.6 - 3.11 also compare the performance of MURT-LL with the OSPF scheme that does not take into account either grooming or the lifetime of traffic. As can be seen from these figures, the distance between the curves of MURT-LL and OSPF becomes quite obvious as traffic load increases. The improvement of MURT-LL on blocking probability over the OSPF scheme can be as high as 10% in our simulation environment. Also as can be observed from these figures, the trend of this improvement is that the heavier the load, the more the improvement. With this trend, we believe when the load is higher, the improvement can be higher than 10%.

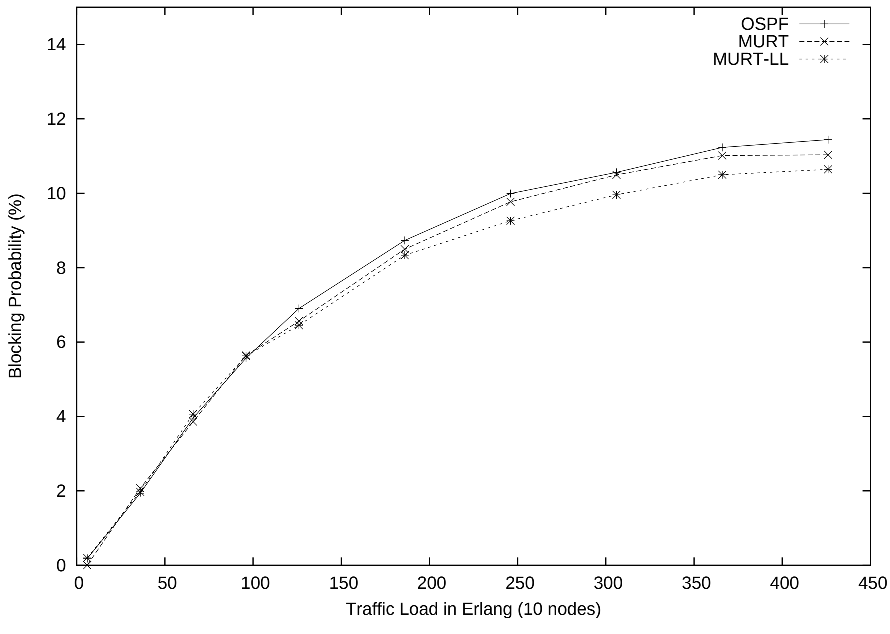


Figure 3.6: Blocking probability for Network 1

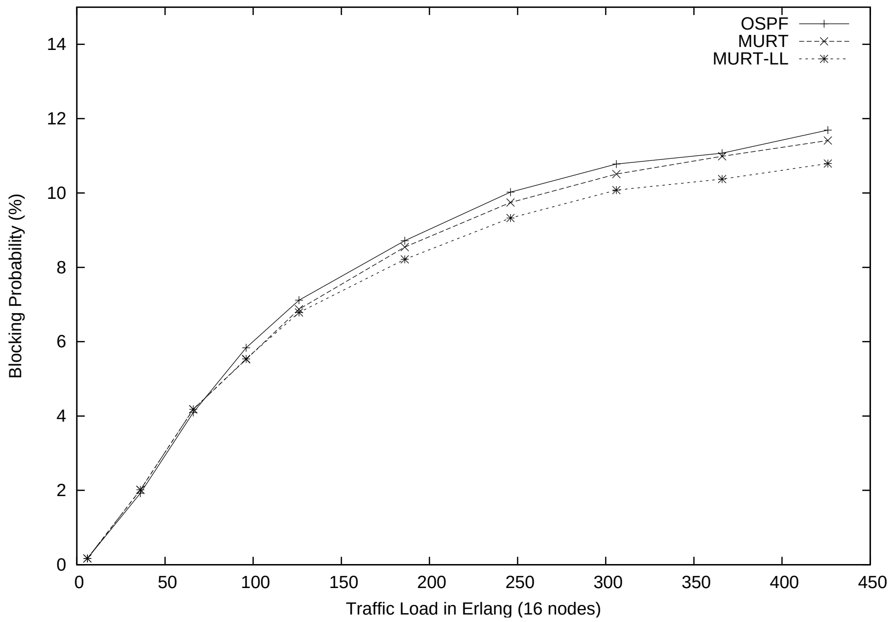


Figure 3.7: Blocking probability for Network 2

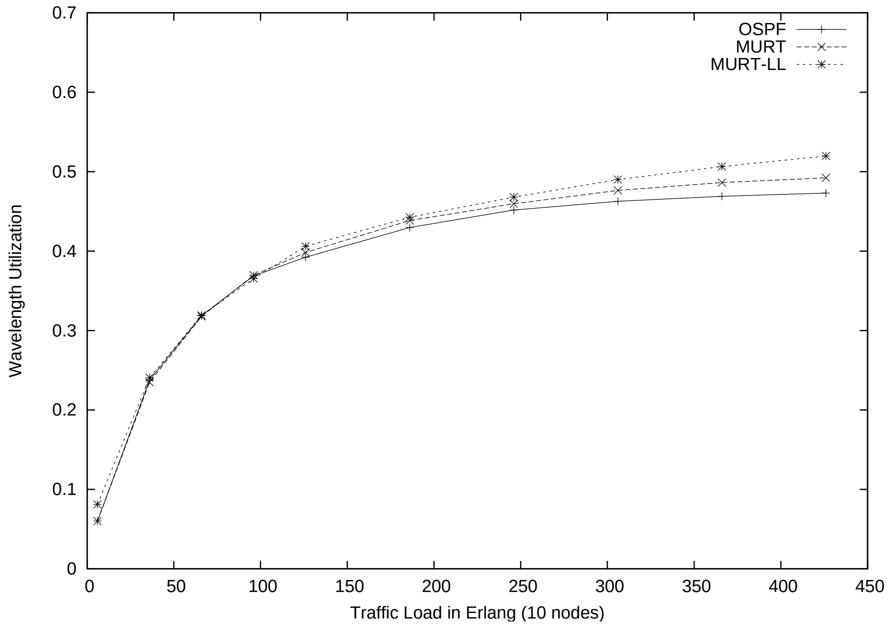


Figure 3.8: Wavelength Utilization for Network 1

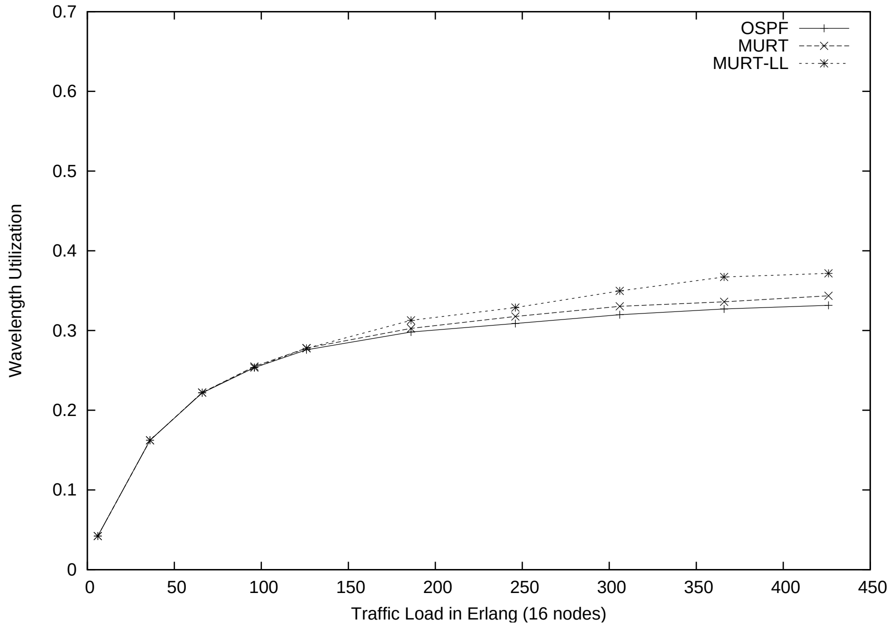


Figure 3.9: Wavelength Utilization for Network 2

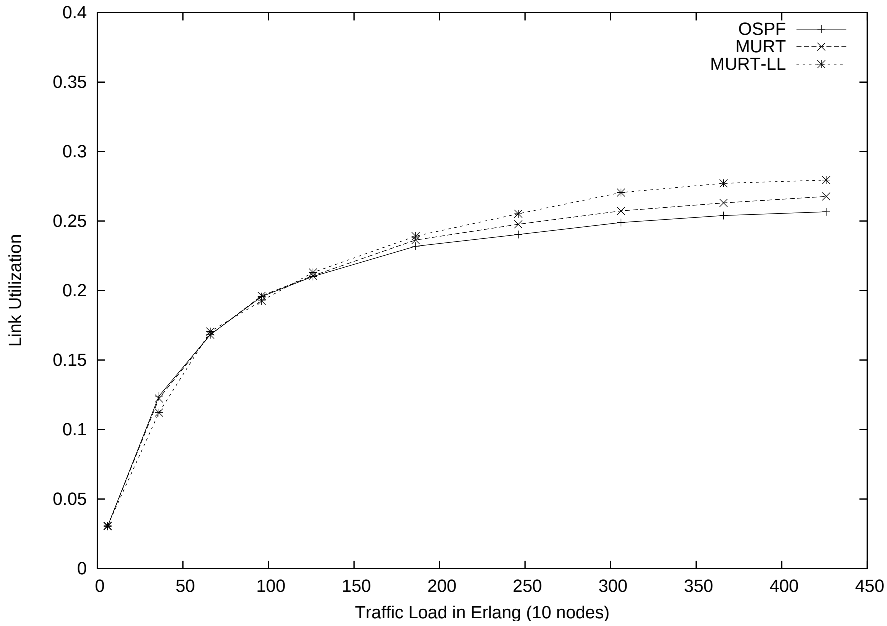


Figure 3.10: Link Utilization for Network 1

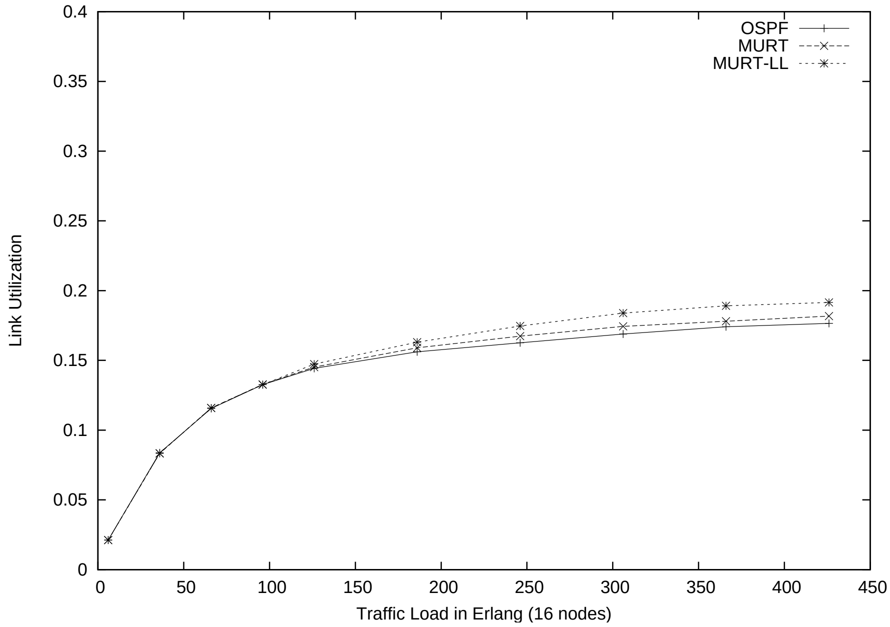


Figure 3.11: Link Utilization for Network 2

3.4 Summary

In this chapter, we improve the MURT scheme introduced in Chapter 2 by considering the effect of long-lived traffic on network performance. In this new routing algorithm, called MURT-LL, long-lived traffic flow is detected by counting the total number of packets belonging to the flow. The effect of resource usage is evaluated and actions are taken based on the results. Simulation results show that the MURT-LL algorithm can further help to reduce blocking probability and enhance bandwidth utilization of the network as well. In general, the improvement can be as high as 10% as compared with the normal OSPF scheme that does not consider either grooming or traffic lifetime for routing over virtual topology.

Chapter 4

Conclusions and Further Research

4.1 Conclusions

Optical networks are implemented worldwidely to accommodate the increasing traffic load and various traffic patterns. Wavelength division multiplexing (WDM) receives great research focus especially because of its flexible and efficient exploiture of the huge bandwidth capacity inherent in optical fibers. Some key techniques of WDM networks arise recently such as virtual topology design, grooming policy and routing algorithm and wavelength assignment (RWA). These problems have been studied extensively. For example, traffic routing is a classical problem and many algorithms exist for it. However, the specialty of traffic routing on virtual topology of a WDM network and the combined consideration of routing and grooming policy have not received much attention as the above three problems. This problem has been the focus of this thesis.

The thesis begins with a background study of WDM networks, including the construction of WDM networks and the integration strategies for IP over WDM. Then, a literature review of basic function blocks of WDM networks is made. RWA, grooming and traffic routing are partitioned into subproblems and discussed respectively. In particular, node architecture of WXC supporting traffic grooming is introduced to illustrate that multiple traffic flows with the same source and destination can be groomed to an existing lightpath.

A routing algorithm considering grooming policy, called MURT, is proposed in Chapter 2. This algorithm takes into account the special situations for routing on virtual topology, which is such routing needs to choose a logical link from possibly multiple logical links between end nodes of them. Since a lightpath is established dynamically, current selection of routing path can affect the accommodation of future connection requests greatly. MURT is proposed as a heuristic solution, which chooses the lightpath with the most wavelength occupancy. By simulation, the performance of MURT is investigated. The results show that by considering wavelength occupancy in routing algorithm and combining routing with grooming policy, network performance expressed as blocking probability, wavelength utilization and link utilization can be improved.

In Chapter 3, an algorithm called MURT-LL extending MURT is proposed and investigated. In the MURT-LL, the lifetime characteristic of traffic is considered. Particularly, in this algorithm, the effect of a long-lived connection affects network resource redistribution is used. If the effect is positive, it is protected; if the effect is negative, it is ameliorated as much as possible. Simulation results show that the actions taken in MURT-LL specially for long-lived traffic can further benefit network performance.

4.2 Further Research

While the MURT and MURT-LL solutions have shown to be able to improve network performance over existing OSFP routing solution, they may suffer from scalability limitations. System scalability is limited by the calculation of wavelength occupancy. The calculation of wavelength occupancy for each wavelength is pushed to source nodes and its complexity increases as the number of nodes and the number of wavelengths on each fiber link increase. In addition, in distributed-control networks, collection of information about wavelength occupancy is time-consuming and the information may be out of date as compared with central-control networks. For these, further research may be conducted to improve the scalability of the proposed schemes.

In the work presented in this thesis, wavelength utilization obeying the wavelength continuous constraint is assumed. This constraint simplifies the situations discussed in the thesis. However, wavelength converters may be used in practice although they increase network cost. Wavelength converters make the network model become much more complex than that discussed in the thesis. Thus, traffic routing on grooming policy and optimization of long-lived traffic flows in such a network situation needs further research.

Another remaining problem is that, for a traffic flow, only single-path routing is considered in the thesis. This is because a traffic connection is the least unit to be groomed on a lightpath and cannot be divided into several lower speed connections and routed separately from the source to the destination. In addition, the data traffic on a connection request should always follow the same route. Nevertheless, a lot of research activities have been conducted in the literature focusing on multiple routing and some interesting results have been reported. Hence, the study of multi-path grooming can be potentially a challenging research topic.

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