Dynamic Provisioning of Heterogeneous Unicast/Multicast Traffic in IP-Centric WDM-Based Optical Networks

by

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Abstract

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This thesis considers the problem of dynamically provisioning heterogeneous unicast/multicast traffic in next-generation IP-Centric WDM networks. Specifically, this work examines, through computer simulation and modeling, the technological requirements and assesses the performance analysis and feasibility for implementing next-generation data-centric optical networks capable of supporting real-time unicast as well as emerging multicast applications. Provisioning of either unicast or multicast connections requires algorithms for route (paths) selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route(s).

Specifically, this work addresses the implementation issues of the path(s) selection mechanism of the traffic-engineering problem in such a network. Methodologies and associated routing algorithms for computation of unicast/multicast full wavelength

channels as well as low-rate traffic streams are devised and outlined. Specifically, this work focuses on developing and implementing reliable, unified constraint-based dynamic routing models and algorithms within the generalized MPLS framework (GMPLS), to support real-time provisioning of unicast/multicast full wavelength optical channels as well as low-rate streams (sub-wavelength).

To implement our overall objectives, this thesis work is divided to two main phases: (1) Dynamic provisioning of unicast traffic only with the main goal of using the optimization procedures and performance results obtained in this phase as guidelines for the ultimate objective of dynamically provisioning both unicast and multicast traffic. (2) Dynamic provisioning of heterogeneous unicast and multicast traffic.

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Chapter 1

1. Introduction

1.1 Introduction

The phenomenal growth in Internet traffic along with the abundance of transmission capacity propelled by the explosion of wavelength-division multiplexing (WDM) technology and the rise of optical communication systems has signaled the beginning of a new networking paradigm where the vision of integrating data and optical networking seems to be indispensable. While IP has emerged as the primary network layer technology, recent advances in optical technology are now transforming the optical layer from a static transmission facility into a dynamically reconfigurable network. There is an emerging consensus that a simplified, two-tiered architecture combining the strengths of both IP and optical transport in which IP can be implemented directly over WDM, bypassing all of the intermediate layer technologies, is the key to realizing such a vision [1][1][2][3][4][5][6][7][8].

Today's core network architecture model has four layers: IP and other content-bearing traffic, over ATM for traffic-engineering, over SONET for transport, over WDM for fiber capacity. This approach has functional overlap among its layers, contains outdated functionality, and typically suffers from the lowest common denominator effect where any one layer can limit the scalability of the entire network. When first conceived, this layering made sense, but as IP and WDM evolve, the ATM and SONET/SDH layers are becoming superfluous.

The notion of supporting "data directly over optics" (the two layer model; IP-over-WDM) has been fueled by the promise that elimination of unnecessary network layers will lead to a vast reduction in the cost and complexity of the network. The two-layer model, which aims at a tighter integration between the IP and optical layers, offers a series of important advantages over the current multi-layer architecture. In this model, the Optical Transport Network (OTN) consists of multiple optical cross-connects (OXCs) interconnected via WDM links in a general mesh topology. Clients, e.g., IP/MPLS label switched routers (LSRs), are attached to the OXCs through wavelength ports and are connected to their peers over dynamically switched optical channels spanning potentially multiple OXCs. IP-based Multi-protocol label switching (MPLS) and its extension Generalized MPLS (GMPLS) have been proposed as the integrating structure between IP and optical layers [4][5][6][8][9][10][11][12].

Several industrial organizations, including the Internet Engineering Task Force (IETF) and the Optical Internetworking Forum (OIF) have already proposed several architectural options on how IP routers must interact with the optical layer to achieve end-to-end connectivity, including overlay, augmented, and peer-to-peer models (interconnection models) [4][5][6][7][8][9]. The simplest is to treat the optical layer as completely separate from the IP layer. In this "overlay" model, the optical layer provides point-to-point connections (lightpaths) to the IP domain. The client routers request high-bandwidth connections from the optical network, via a well-defined signaling and routing interface, referred to as User to Network Interface (UNI), and are provided with no knowledge of the optical network topology or resources. A more sophisticated model that offers a tighter integration between IP and optical layers (peer model) collapses the two layers into a single integrated layer managed and traffic engineered in a unified manner.

A critical issue for realizing such intelligent optical networks is how to provide the desired features of rapid provisioning/restoration and automated capabilities between the optical layer and the client layers. It is widely accepted that the best way to achieve this is to adapt the IP topology self-discovery and routing capabilities to the optical network environment. Current research focuses on the use of distributed management schemes such as multi-protocol label switching (MPLS) to provide the control plane necessary to ensure automated provisioning and maintaining connections and managing network resources. In this type of application, the label is the wavelength of the incoming signal; hence, the term multi-protocol lambda switching (MPλS) is more commonly used. The main goal of this initiative is to provide a framework for real-time provisioning of optical channels, through combining recent advances in Multi-protocol label switching (MPLS) traffic-engineering control plane with emerging optical switching technology in a hybrid IP-centric optical network.

Most of the GMPLS-based routing and signaling algorithms, which have been reported by the standards bodies and corresponding research activities, were mainly developed to provision unicast traffic. However, as networks evolve to support more bandwidth-intensive applications, and as rich multimedia and real-time services become more popular, next generation networks, as this work will show, are expected to support both unicast and multicast applications (e.g., multiparty conferencing, software and video distribution, and distributed computing, etc.).

1.2 Thesis Motivation

It is evident that a sizeable portion of future traffic demands will be heterogeneous in nature and hence the network is required to support different bandwidth and service requirements. Practically, in most of these cases, the bandwidth requirement is only a fraction of the total bandwidth of a single WDM channel. Therefore a major shortcoming in current WDM networks is the large disparity between the coarse/fixed granularity bandwidth offered by the optical layer to clients (full wavelength level, e.g., OC-48 (2.5 Gbps), OC-192 (10 Gbps) and OC-768 (40 Gbps)) and the bandwidth requirement of a typical connection request, which is only a fraction of a wavelength (e.g., STS-1 (51 Mbps), OC-3 (155 Mbps), OC-12 (622 Mbps), etc.). Clearly, traffic demands with finer bandwidth granularity are the rule and those requiring full wavelength capacity are the exceptions. In addition, in networks of practical size, the number of source-destination traffic connections is still an order of magnitude higher than the number of available wavelengths.

In order to efficiently utilize the capacity of each wavelength channel (lightpath), several independent lower-speed traffic streams must be multiplexed onto a single lightpath. The process of combining low-rate traffic streams onto high-capacity optical channels (lightpaths) is known in the literature as "traffic grooming". To support traffic grooming, the cross-connect fabric of each optical node should have the capability of switching traffic at the wavelength granularity as well as at finer granularities.

Most early work on traffic grooming has focused on SONET rings, where traffic is often static and known in advance. More recently, traffic grooming in mesh-based WDM networks has attracted an increased amount of research effort. Most of these studies have assumed only unicast traffic. However, as networks evolve to support more bandwidth-intensive applications, and as rich multimedia and real-time services become more popular, next generation networks are expected to support both unicast and multicast applications (e.g., multiparty conferencing, software and video distribution, and distributed computing, etc.). To support multicasting at the physical layer of WDM networks, the concept of a light-tree has been introduced. A light-tree is a point-to-multipoint extension of a lightpath, where the branching nodes of a light-tree are equipped with optical power splitters.

Similar to the case of unicast traffic demands, some of these multicast applications require only a fraction of the channel capacity (for example, HDTV needs only 20 Mbps). Thus, dedicating an entire light-tree to a single or few users may lead to a huge waste of network resources. To improve the network throughput, one would need to bundle several low-rate unicast and multicast traffic streams efficiently onto a single high capacity light-tree so that the number of wavelengths that have to be processed at each node is minimized. Hence, the problem of multicast traffic grooming has become an important area for future research work. Furthermore, as network architectures transition from ring-based to mesh-based, both unicast and multicast traffic grooming in mesh-based networks will become an important extension to current ring-based grooming algorithms. Today's networking infrastructure provides only limited static point-to-point multicast services connectivity at the IP layer. However, next generation networking infrastructure, as this thesis will show, are expected to support dynamic and survivable unicast and multicast traffic demands.

1.3 Thesis Statement

This thesis considers the problem of dynamically provisioning heterogeneous unicast/multicast traffic in next-generation IP-Centric WDM networks. Specifically, this work examines, through computer simulation and modeling, the technological requirements and assesses the performance analysis and feasibility for implementing next-generation data-centric optical networks capable of supporting real-time unicast as well as emerging multicast applications. Provisioning of either unicast or multicast connections requires algorithms for route (paths) selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route(s).

Specifically, this work addresses the implementation issues of the path(s) selection mechanism of the traffic-engineering problem in such a network. Methodologies and associated routing algorithms for computation of unicast/multicast full wavelength channels as well as low rate traffic streams are devised and outlined. Specifically, this work focuses on developing and implementing reliable, unified constraint-based dynamic routing models and algorithms within the generalized MPLS framework (GMPLS), to support real-time provisioning of unicast/multicast full wavelength optical channels as well as low-rate streams (sub-wavelength).

Since the proposed two-layer model considered in this work comprises two independent topologies as well as two independent resource usage information; namely, the client layer (IP/MPLS layer) logical topology and its resource usage information (e.g., the electronic router forwarding speed, its throughput, and the sub-lambda connection requests data base), and the optical layer physical topology and its associated resource usage information (e.g., the number of fibers connecting two adjacent physical nodes, the number of wavelength channels per fiber, and the optical cross-connect throughput). Thus, there are two approaches for provisioning a given connection request:

1) Conventional sequential routing approach using the overlay model where most of existing routing studies deals only with sequential routing where the cost function takes into account the recourse usage information at either the logical topology

(IP resources) or at the optical layer, but not at both. Typically, routing in IP over WDM networks has been separated into routing at the IP layer, taking only IP layer information into account, and wavelength routing at the optical layer, taking only optical network information into account.

2) Integrated routing approach where the combined knowledge of resource and topology information in both the IP and optical layers are taken into account. One possibility that has been considered by the IETF is to consider both routers and OXCs as being in the same domain, and to run an OSPF-like protocol on both routers and OXCs (peer interconnection model). Implementing a practical integrated routing approach utilizing the peer model does, however, present a scalability problem due to the amount of state and control information to be handled by any network element within an administrative domain. This means that a significant amount of state and control information must flow between the IP and optical layers, making the development of this model more time-consuming and complex. Compounding the problem is the fact that it is highly unlikely that a service provider who owns the OTN would ever give a client full access to the topology and resources of the optical network.

To implement our overall objectives, this thesis work is divided to two main phases: (1) Dynamic provisioning of unicast traffic only with the main goal of using the optimization procedures and performance results obtained in this phase as guidelines for the ultimate objective of dynamically provisioning both unicast and multicast traffic. (2) Dynamic provisioning of heterogeneous unicast and multicast traffic.

In the first phase of this work, we study the problem of real-time provisioning of unicast traffic. Then we extend the research work to study the problem of traffic grooming in WDM networks. We explore the potential of implementing a practical integrated routing approach by introducing a novel, simple and scalable optical networking paradigm where most of the networking functionalities and intelligence are shifted down to the optical layer, including supporting selective provisioning/restoration of diverse traffic granularities entirely on the optical layer's terms.

We then use the proposed optical-layer unified model to develop novel integrated routing approaches for IP-over-WDM networks. Specifically, we devise an adaptive integrated routing approach that takes into account the combined topology and resource usage information at both the IP and WDM layers. Since the optical layer is now aware of both the logical and physical topologies and connectivity, it is able to serve calls by selecting a mixture of existing lightpaths and setting up new lightpaths in a way that optimizes resource usage. This introduced the important concept of hybrid provisioning that has allowed us to efficiently provision multicast traffic. The prime difference between the conventional sequential routing algorithms that utilize the overlay model, and the routing problem considered in this work, is that instead of separating routing at each layer, we consider the routing of LSPs taking into account the combined knowledge of resource and topology information in both the IP and optical layers.

The second phase of this thesis focuses on implementing solutions for the dynamic provisioning of both unicast and multicast traffic. Specifically, we address the problem of dynamically provisioning both low-speed unicast and multicast connection requests in mesh-based WDM optical networks. Several routing/provisioning schemes are presented to dynamically provision both unicast and multicast connection requests. A constraint-based grooming strategy is devised to utilize the overall network resources as efficiently as possible. Based on this strategy, several different sequential multicast grooming heuristics are first presented. Then, using a novel optical layer-based unified control plane, we devise a hybrid grooming approach and combine it with sequential approaches to achieve a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches.

To achieve our objective, we decompose the problem into four sub-problems: 1) Routing problem. 2) Design of a light-tree based logical topology. 3) Provisioning problem. 4) Traffic-grooming problem. The simulation results of the proposed schemes are compared with each others and with those of conventional non-grooming approaches. To the best of our knowledge, this is the first detailed work to address and examine the problem of grooming dynamic multicast traffic demands.

Finally, we investigate the problem of dynamic provisioning of survivable heterogeneous unicast and multicast traffic in WDM networks. This problem can be divided to two sub-problems. (1) Routing sub-problem, i.e., finding primary and backup trees. (2) Wavelength assignment sub-problem. Therefore, in order to successfully provision a survivable session, the two sub-problems must be successfully solved. Failing in assignment wavelengths to primary and backup trees can be solved by increasing the number of wavelengths in the network, however, failing in finding a backup route/tree for the unicast/multicast session can never be solved and will lead to blocking the session. In fact, finding link-disjoint route/trees depends on the heuristics used to find the multicast tree. The less optimum the heuristic, the more difficult is to find link-disjoint primary and backup trees. Therefore, we propose new protection schemes that optimize the routing heuristics to provision survivable unicast and multicast connection requests in WDM-mesh networks.

Chapter 2

2. Dynamic Real-Time Provisioning in Mesh-Based WDM Networks: Analytical Modeling

2.1 Introduction

In wavelength-routed all optical networks, a connection between two nodes must use the same wavelength along a chosen route [1]. This requirement is referred to as the wavelength continuity constraint and makes networking in all optical wavelength-routed networks different from the conventional circuit switched networks. The problem of routing and wavelength assignment (RWA) has extensively been studied in the literature [2][3] and it has been shown to be NP-complete [3][4]. The traditional way to solve this problem is to separate it into two sub-problems, namely routing sub-problem and wavelength assignment sub-problem. Several heuristic algorithms have been proposed and the call-blocking performance of these algorithms was evaluated through simulations [5].

Analytical models for analyzing the performance of all-optical wavelength-routed networks have been proposed in [4][6][7][8][9]. In [8], the author uses a generalized reduced load approximation to compute the end-to-end blocking probabilities for fixed routing and least loaded routing. Random wavelength assignment scheme was used throughout the analysis due to its simplicity. The model is shown to give good results only for fairly small networks and its complexity grows exponentially with the hop length. In [9], a new analytical technique, based on the inclusion-exclusion principle from combinatorics, was proposed for the analysis of all-optical networks with no wavelength conversion and random wavelength assignment. The authors propose two models of low complexity. The first model improves the model proposed in [10] in that the complexity of calculation is independent of the hop length and scales only with the capacity of the link. The second model shows that it is accurate for sparse networks. The authors also extend their models to analyze fixed routing and least loaded routing, both with random wavelength assignment scheme.

Analytical models for the first-fit wavelength assignment have been proposed in [4][6][7]. Here, the layered-graph approach proposed in [10] is used to simplify the lightpath establishment. In this approach, each layer corresponds to a single wavelength and the number of layers corresponds to the number of wavelengths. This can alleviate the difficulties incurred by the wavelength continuity constraint by simultaneously considering the routing and wavelength assignment on each layer. Traffic, which is blocked on one layer, overflows into the second layer and versions of overflow traffic model are used. In [4], the authors assume the arrival process on each link to be a BPP

(Binomial-Poisson-Pascal) distribution and they also model the overflow traffic to follow a BPP distribution. The authors of [6] developed a new analytical model to compute the blocking probabilities for fixed routing and fixed alternate routing with first-fit wavelength assignment by adopting the layered-graph approach in their analysis, assuming the arrival and the overflow processes to follow a Poisson distribution.

In this chapter, we present a new analytical model to compute approximate blocking probabilities in all-optical wavelength-routed networks. The model is based on the layered-graph approach and models the arrival rate as a Poisson distribution. The model utilizes the moment matching techniques; specifically the Equivalent Random Method (ERM) to model the overflow traffic between different wavelength layers and between alternate routes, such method has been successful tools for the analysis of overflow systems. The model studies the blocking performance of fixed routing (FR), fixed-alternate routing (FAR) and fixed alternate routing with trunk reservation (FARwTR). The performance of the analytical model is compared with those of the conventional models that use heuristic algorithms. The remainder of this chapter is organized as follows. In section 2.2 we present the network and traffic model assumptions; section 2.3 presents the fixed routing with First-Fit wavelength assignment scheme. Fixed alternate routing and fixed alternate routing with trunk reservations are presented in section 2.4, and section 2.5 presents the numerical results. Finally, the chapter concludes in section 2.6.

2.2 Network and Traffic Model Assumptions

In this section, we state the assumptions about the network and the traffic used in our model for calculating the path blocking probability of an all-optical network with no wavelength converters. A network with N nodes and J links can be represented by a directed graph $G\ (N,\ J)$. Each link has the same number of wavelengths W. Calls arrive according to a Poisson process and the duration of each call is exponentially distributed with unit mean.

Let λ be the total traffic load offered to the network, a_r be the offered load to the r^{th} *s-d* connection pair, $R = \{r_1, r_{2,} .... r_{N(N-1)}\}$ be the set of all routes in the network, $E = \{1,2.......J\}$ be the set of all links, and $W = \{\lambda_1, \lambda_2, ..., \lambda_W\}$ is the set of all wavelengths.

In our approach the problem of computing path blocking on a particular wavelength is reduced to computing approximate blocking probability in a circuit switched network [11][12]. We extend the layered-graph approach [10], to develop an approximate analytical model for the path blocking. By using this layered approach, the RWA problem is reduced to only finding an end-to-end path on a wavelength between the *s-d* pair. The search for a path and a wavelength may be viewed as a search over a sequence of W logical paths, where a logical path is a combination of a physical path and a particular wavelength. If the logical path under consideration is available, then the connection is established, otherwise the connection request overflows to the next logical path. Here, we use the moment matching techniques, specifically the Equivalent Random Method (*ERT*) [13] to model the overflow traffic between different wavelength layers.

Let:

$a_{r_i}^{\lambda_k}$: The arrival rate on route r_i on wavelength layer λ_k.

$B_j^{\lambda_k}$: The link blocking probability on link j on wavelength λ_k.

$\alpha_j^{\lambda_k}$: The traffic load on link j on wavelength λ_k.

$L_{r_i}^{\lambda_k}$: The path blocking probability on route r_i on wavelength layer λ_k.

If we consider a network with F fibers per link, the number of idle circuits on link j on wavelength λ_k can be viewed as a birth-and-death process given that the traffic arrival follows a Poisson distribution.

$$P_m = Prob\ \{\boldsymbol{m} \text{ circuits are used}\} = \frac{(\alpha_j^{\lambda_k})^m}{m!}[1+\sum_{n=1}^{F}\frac{(\alpha_j^{\lambda_k})^n}{n!}]^{-1} \tag{2.1}$$

$B_j^{\lambda_k} = Prob\ \{\boldsymbol{F}$ circuits are used on link j on wavelength $\lambda_k\} = P_F$

If the number of fibers per link is one, then:

$$B_j^{\lambda_k} = \frac{\alpha_j^{\lambda_k}}{1+\alpha_j^{\lambda_k}} \tag{2.2}$$

On the other hand, if the traffic offered to a link does not follow a Poisson distribution, it is defined by its peakedness $Z = \frac{m}{v} \neq 1$ where m is the mean and v is the variance of the offered traffic. Thus, if (A, N, Z) characterizes the system, where A is the offered traffic and N is the number of trunks per link; using the *ERT*, we transform this system into the following system $(\frac{A}{Z}, \frac{N}{Z}, 1)$ and thus the link blocking is computed using the *Erlang B* system [13].

2.3 Fixed Routing

2.3.1 Fixed Routing with First-fit Wavelength Assignment

The traffic rate on link j on wavelength λ_k can be approximated [11][12] by:

$$\alpha_j^{\lambda_k} = \sum_{r:j\in r} a_r^{\lambda_k} \cdot \prod_{m\in r-\{j\}} (1-B_m^{\lambda_k}) \qquad \forall r \in R \tag{2.3}$$

Here, the idea of approximation is simple to explain: suppose a Poisson stream of rate $a_r^{\lambda_k}$ is thinned by a factor $(1-B_m^{\lambda_k})$ at each link $m \in r-\{j\}$ on wavelength graph λ_k before being offered to link j. If this thinning could be assumed independent from link to link and over all routes passing through link j, then the traffic offered to link j would be Poisson at rate $\alpha_j^{\lambda_k}$.

The path blocking on route r_i on a wavelength λ_k can be computed by using the link distribution:

$$L_{r_i}^{\lambda_k} = 1 - \prod_{j\in r_i} (1-B_j^{\lambda_k}) \tag{2.4}$$

Note that $L_{r_i}^{\lambda_k}$ is the blocking probability on route r_i on wavelength layer λ_k when the offered traffic to route r_i is $a_r^{\lambda_k}$. Here, a fraction of $a_{r_i}^{\lambda_k}$ overflows to wavelength λ_{k+1} with probability $L_{r_i}^{\lambda_k}$. Hence,

$$a_{r_i}^{\lambda_{k+1}} = a_{r_i}^{\lambda_k} . L_{r_i}^{\lambda_k} \tag{2.5}$$

The total blocking on route r_i is then approximated by:

$$L_{r_i} = \prod_{k=1}^{W} L_{r_i}^{\lambda_k} \tag{2.6}$$

Next we show the numerical solution to this problem. Due to the non-linear relation between equations (2.1) and (2.3), an iterative procedure is used to solve this system.

Table 2.1: Calculation of L_R for fixed routing

1. Initialization:

- $\tilde{L}_{r_i}^{\lambda_k} = 0$ for $i = 1.......N(N-1), \quad k = 1......W$
- $a_{r_i}^{\lambda_k} = 0$ for $i = 1.......N(N-1), \quad k = 2.......W$
- $a_{r_i}^{\lambda_1} = \frac{\lambda}{N(N-1)}$ for $i = 1.......N(N-1)$
- $\alpha_j^{\lambda_k} = 0$ for $j = 1.........J, \quad k = 2........W$
- $\alpha_j^{\lambda_1} = \sum_{r:j\in r} a_r^{\lambda_1}$ $\forall r \in R$

2. Repeat for all wavelengths:

2.1- determine $B_j^{\lambda_k}$ for $j = 1......J$ **from (1)**

2.2- determine $\alpha_j^{\lambda_k}$ for $j = 1......J$ **from (3)**

2.3- determine $L_{r_i}^{\lambda_k}$ for $i = 1......N(N-1)$ **from (4). If** $\max_i |L_{r_i}^{\lambda_k} - \tilde{L}_{r_i}^{\lambda_k}| < \varepsilon$ **then compute** $a_{r_i}^{\lambda_{k+1}}$ for $i = 1........N(N-1)$ **from (4), compute** $\alpha_j^{\lambda_{k+1}} = \sum_{r:j\in r} a_r^{\lambda_{k+1}}$ $\forall r \in R$, for $j = 1......J$, **and go back to step 2. If not converge, then** $\tilde{L}_{r_i}^{\lambda_k} = L_{r_i}^{\lambda_k}$ for $i = 1......N(N-1)$ **and go back to 2.1.**

2.3.2 Fixed Routing with Random Wavelength Assignment

In this section, we extend our model to analyze all-optical wavelength-routed networks for fixed routing and Random Wavelength Assignment.

In Random wavelength assignment, each wavelength is equally likely to be selected by any incoming call request; thus, we define the probability of selecting a wavelength from a set of W wavelengths to be:

$$P(\lambda_i \text{ is seletced}) = \frac{1}{|W|}, \forall \lambda_i \in W$$

If λ is the total traffic in the network, then the traffic per s-d pair on a given wavelength graph λ_k is initially given by: $a_{r_i}^{\lambda_k} = \frac{\lambda}{N(N-1)} \times P(\lambda_k \text{ is selected}) = \frac{\lambda}{N(N-1)} \times \frac{1}{|W|}$.

Note that, a blocked call on a wavelength layer λ_k overflows to any wavelength $\lambda_{k'} \in W - \{\lambda_k\}$ with equal probability, $p = \frac{1}{|W|-1}$, $if\ |W| > 1$

One can estimate now the traffic rate on any route r_i on any wavelength layer λ_k using the following recursive equation:

$$a_{r_i}^{\lambda_k,(l)} = a_{r_i}^{\lambda_k,(l-1)} \times (1 - L_{r_i}^{\lambda_k,(l-1)}) + \sum_{m \in W - \{\lambda_k\}} a_{r_i}^{\lambda_m,(l-1)} \times p \times L_{r_i}^{\lambda_m,(l-1)} \qquad (2.7)$$

The first half of the sum in equation (2.7) accounts for the remaining traffic on route r_i, while the second half equates the overflow traffic from the remaining wavelengths in the set. Note that here, traffic on a route r_i on a wavelength $\lambda_{k'} \neq \lambda_k$ overflows with probability p to route r_i on wavelength λ_k.

A similar numerical procedure to the ones shown in Table 2.1 is followed; here, the route traffic is computed each time using equation (2.7).

2.4 Fixed Alternate Routing

2.4.1 Fixed Alternate Routing with First-fit Wavelength Assignment

In Alternate Routing, each source-destination pair is assigned a set of paths. The set of paths may be searched in a fixed or adaptive order. Alternate routing improves the performance of the network by allowing a call blocked on a route to try an alternate route with sufficient resources.

Let L be the number of edge-disjoint paths between an s-d pair. On each path, the wavelength set is searched in a fixed order to find a suitable wavelength to establish the connection. In alternate routing, the search for a path and a wavelength may be viewed as a search over a sequence of LW logical paths, where a logical path is the combination of a particular physical route and a particular wavelength. If the logical path under consideration is available, then the connection is established; otherwise the connection overflows to the next logical path.

Based on the same underlying approximation (link blocking independence [13]), we can extend equation (2.3) to compute the link traffic:

$$a_j^{\lambda_i} = \sum_{l=1}^{L} \sum_{r^{(l)}:j\in r^{(l)}} a_{r^{(l)}}^{\lambda_i} \prod_{k\in r^{(l)}-\{j\}} (1 - B_k^{\lambda_i}) \tag{2.8}$$

Where, $a_{r^{(l)}}^{\lambda_i}$ is the traffic intensity on route $r^{(l)}$ on wavelength λ_i

The traffic blocked on the first route overflows to the alternate route, and the traffic intensity on the alternate route on wavelength λ_i is approximated by:

$$a_{r^{(l)}}^{\lambda_1} = a_{r^{(l-1)}}^{\lambda_W} \times L_{r^{(l-1)}}^{\lambda_W} \qquad ,1 = 2.......L \tag{2.9}$$

$$a_{r^{(l)}}^{\lambda_i} = a_{r^{(l)}}^{\lambda_{i-1}} \times L_{r^{(l)}}^{\lambda_{i-1}} \qquad ,i = 2.......W \tag{2.10}$$

$L_{r^{(l)}}^{\lambda_i}$ is the path blocking on the l^{th} alternate route on wavelength λ_i; $L_{r^{(l)}}^{\lambda_i}$ is approximated as in equation (2.4). The overall blocking probability for an s-d pair is:

$$L_{r_i} = \prod_{l=1}^{L} \prod_{k=1}^{W} L_{r_i^{(l)}}^{\lambda_k} \qquad \forall r_i \in R \tag{2.11}$$

2.4.2 Fixed Alternate Routing with Trunk Reservation

Under this scheme, blocking of alternately routed calls is determined by the number of free wavelengths in the alternate path, which is defined as the minimum number of free wavelengths on all the links along the path [14]. In particular, a number *"r"* is chosen such that if the alternate path has fewer than *"r"* free wavelengths, all the alternately routed traffic will be banned on that path. In other words, the last *"r"* free wavelengths are always reserved for the directly routed traffic. The underlying principle of this scheme is to block alternately routed traffic more often on the busy links or paths and to let it be carried by the alternate paths that are not so busy. This actually helps in equalizing the traffic load over the network so that fewer calls will be lost due to local traffic congestion. Furthermore, this scheme helps to protect the directly routed traffic from being blocked due to excessive loading of the alternately routed traffic, because the last *"r"* free wavelengths are always reserved only for the directly routed traffic.

To find the end-to-end blocking probability, we use an approach similar to that of the alternate routing case. In this approach, a link with *W* wavelengths is seen as *W* virtual links where each one corresponds to a wavelength along the link. Thus, we need to find the load offered to each individual virtual link given a trunk threshold *"r"*.

If we consider the case where only one alternate route is allowed (*L=2*), then he offered load could be approximated as follows:

$$\alpha_j^{\lambda_i} = \alpha_j^{\lambda_i,d} + \alpha_j^{\lambda_i,a} \quad \text{for} \quad 0 \le i \le W - r \tag{2.12}$$

$$\alpha_j^{\lambda_i} = \alpha_j^{\lambda_i,d} \quad \text{for} \quad W - r + 1 \le i \le W$$

Where $\alpha_j^{\lambda_i,a}$ and $\alpha_j^{\lambda_i,d}$ are the offered traffic loads to link j on wavelength λ_i form both direct and alternate traffic and they are given by:

$$\alpha_j^{\lambda_i,a} = \sum_{r^{(1)}:j\in r^{(1)}} a_{r^{(1)}}^{\lambda_i} \prod_{k\in r^{(1)}-\{j\}} (1 - B_k^{\lambda_i}) \tag{2.13}$$

$$\alpha_j^{\lambda_i,d} = \sum_{r^{(2)}:j\in r^{(2)}} a_{r^{(2)}}^{\lambda_i} \prod_{k\in r^{(2)}-\{j\}} (1 - B_k^{\lambda_i}) \tag{2.14}$$

The link blocking probability and the end-to-end blocking probability are given by equations (2.2) and (2.4) respectively.

2.5 Performance Evaluation

The accuracy of the proposed analytical model is evaluated via simulation of the mesh-based NSF network. The *NSF* network consists of 14 nodes and 21 physical links (See Figure 2.1). Each adjacent node pair is connected through a bi-directional physical link that consists of F fibers, where each fiber is assumed to have the same number of wavelengths W. We use a dynamic traffic model in which call requests arrive at each node according to a Poisson process with a network arrival rate λ. An arrival session is equally likely to be destined to any node in the network. The session holding time is assumed to be exponentially distributed with mean $1/\mu$. The blocking probability is the metric used to evaluate the network performance. In each simulation run, a large number of requests are generated one after the other, and the results are averaged over many simulation runs.

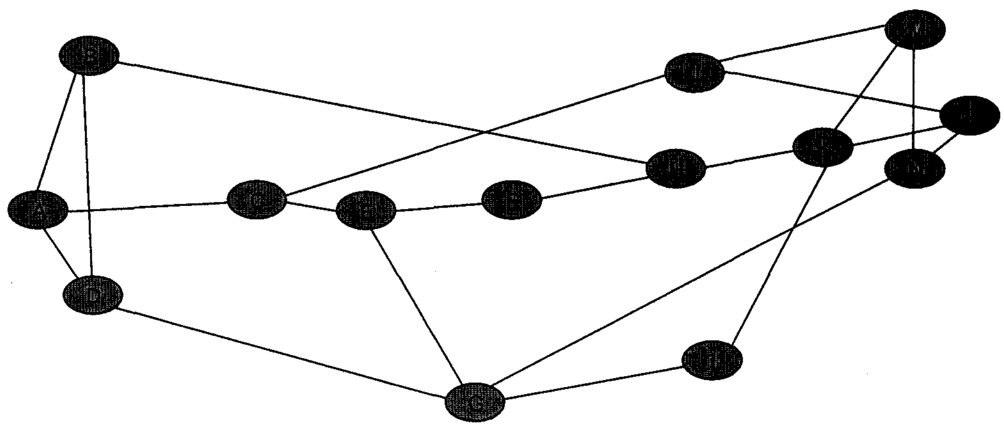

Figure 2.1: NSF Network Topology

We conduct a numerical comparison of the analytical technique against simulation results to study the accuracy of the proposed model. The number of wavelengths per fiber is set to be 4 and 8. Figure 2.2 shows the comparison between the analytical model and simulation results for the NSF network. The first fit wavelength assignment is used. The figure shows the accuracy of the model when the number of wavelengths is 4. On the other hand, when the number of wavelengths becomes 8, the analytical model underestimates the blocking probability. This is due to the fact that the more the number of wavelengths is, the more the traffic overflows between the wavelength layers; and hence the less accurate the overflow traffic is approximated. Nevertheless, the moment matching technique gives a closer estimation of the overflow traffic than the Poisson assumption.

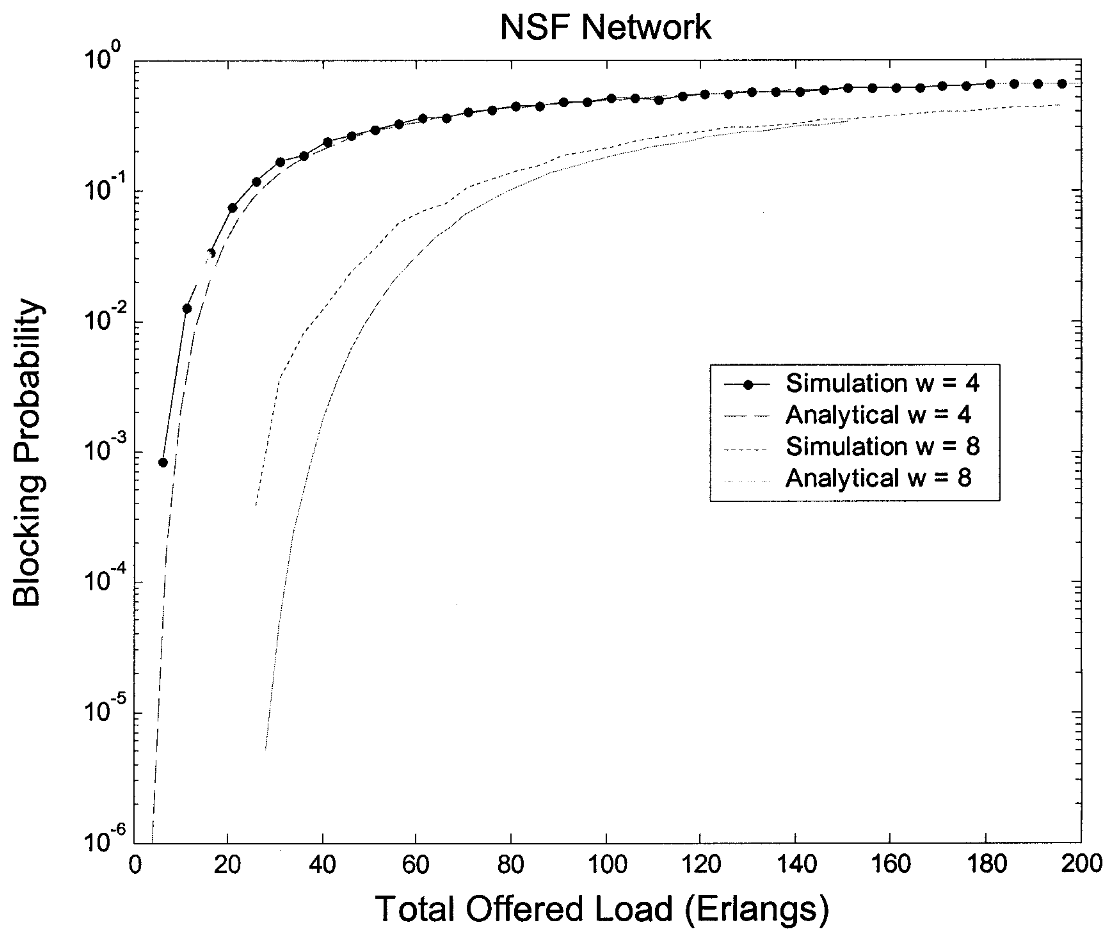

Figure 2.2: FR with FF wavelength assignment

Figure 2.3 shows the same comparison using a different architecture, the ring network. The analytical model here overestimates the blocking probability (the computed approximate blocking probability is less than the blocking probability that was obtained through the simulation); this is due to the fact that in ring architecture, routes usually tend to have more hops; hence, the assumption of link-independency of our model is not as accurate as in mesh networks.

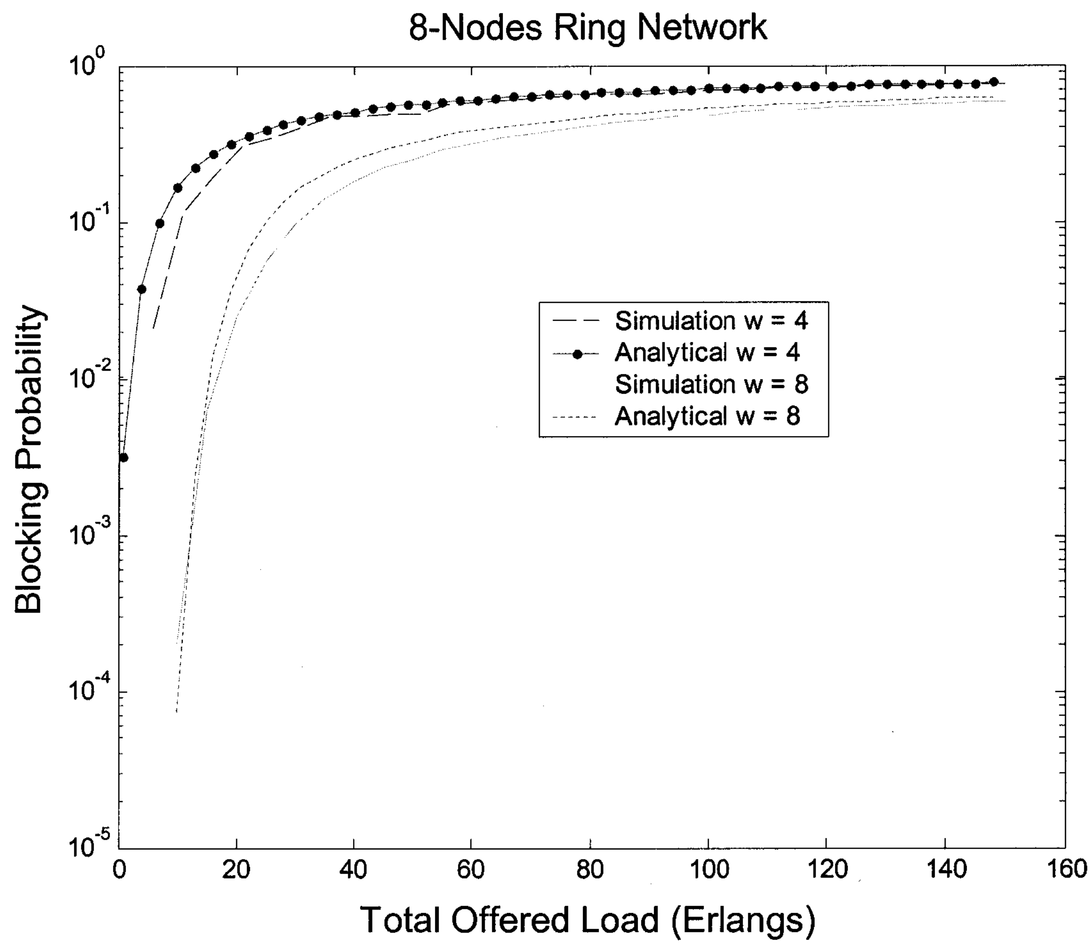

Figure 2.3: FR with FF wavelength assignment (Ring)

Different wavelength assignment schemes were compared analytically and through simulation and results are shown in Figure 2.4 and Figure 2.5. Here we see that our model is also accurate for the random wavelength assignment not only for small networks as opposed to [8], but also for more complex networks like NSF. From the simulation, it is obvious that the *FF* slightly outperforms the Random selection (*RS*) as opposed to the analytical model where at lower load the *RS* slightly outperforms the *FF*.

Figure 2.4 and Figure 2.5 show the results of the fixed alternate routing (*FAR*) versus the fixed routing (*FR*). As shown, fixed alternate routing improves the network performance at light loads due to the flexibility in the routing algorithm. However, as the load increases, alternate routing degrades the blocking performance and the improvement of *FAR* is very limited; this is due to the fact that alternate routing will occupy more transmission resources and thus, at higher loads will prevent direct traffic from being routed and leads to instability. By limiting the flow of the alternately routed traffic, once can overcome the instability problem. Trunk reservation (*TR*) is one technique to improve the performance of alternate routing at higher loads.

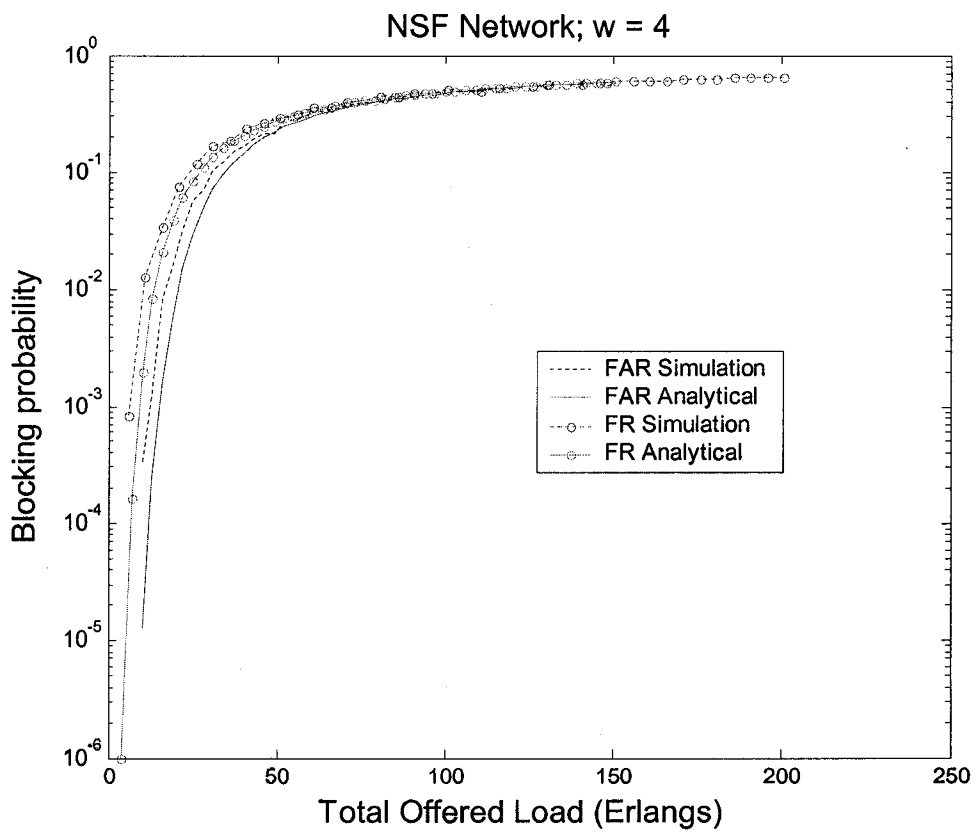

Figure 2.4: FAR and FR with FF wavelength assignment (4 wavelengths)

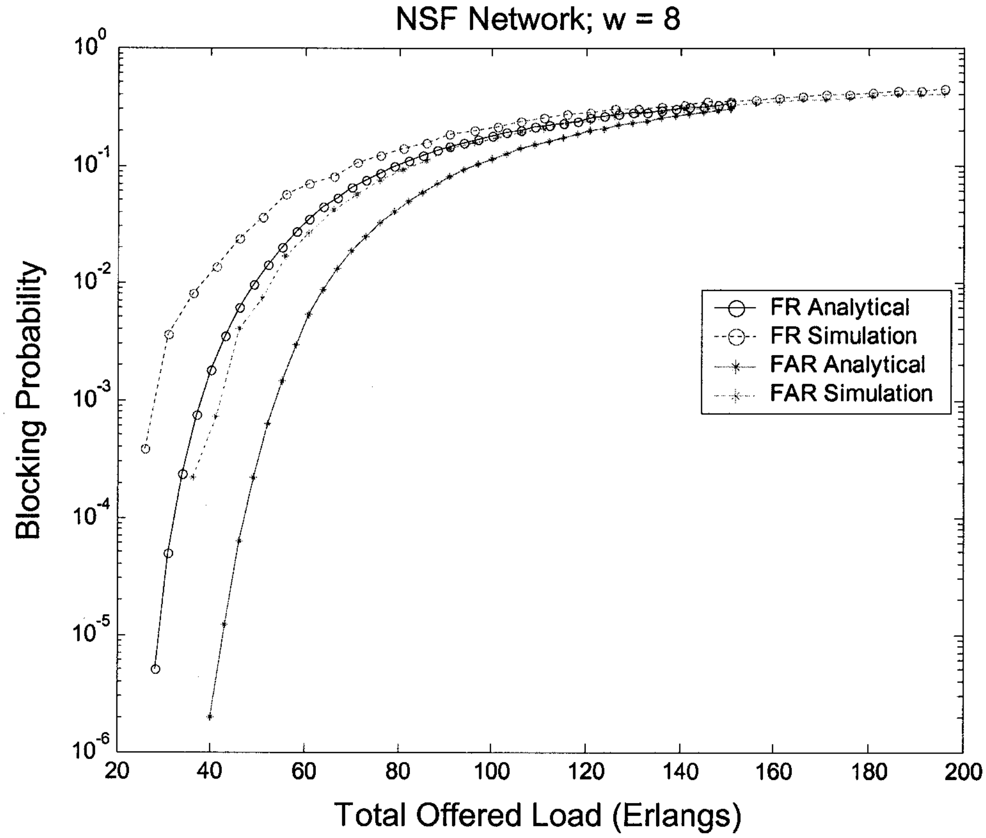

Figure 2.5: FAR and FR with FF wavelength assignment (8 wavelengths)

Figure 2.6 and Figure 2.7 show the analytical comparison between the *FR*, the *FAR* and the *FAR* with *TR*. Figure 2.6 shows that at lower loads, *FAR* routing outperforms the other routing techniques and gives a lower bound on the blocking. Also it is shown in the same figure that the improvement in the blocking performance using *TR*. By decreasing the trunk threshold one can improve the network performance by allowing more resources on the alternate routes to be used by blocked connections. However, Figure 2.7 shows that alternate routing will degrade the performance at higher loads (upper bound on blocking), whereas *FAR* with *TR* can better manage the network resources by selecting the right trunk threshold ($r = 5$ in this case).

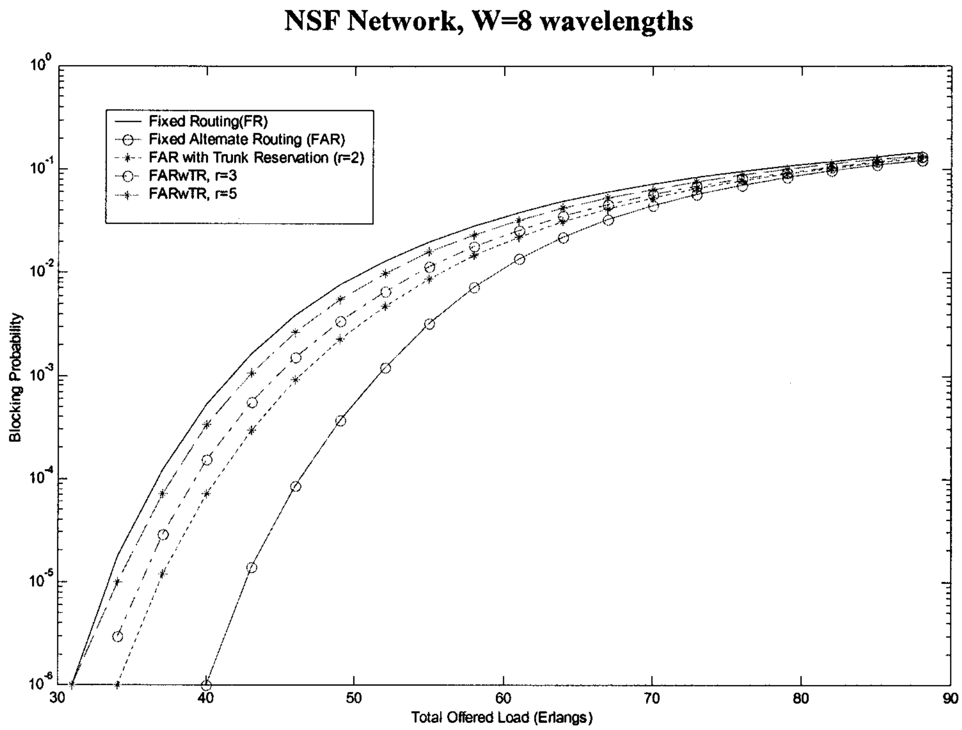

Figure 2.6: FAR with Trunk Reservation (FARwTR) - Low Load

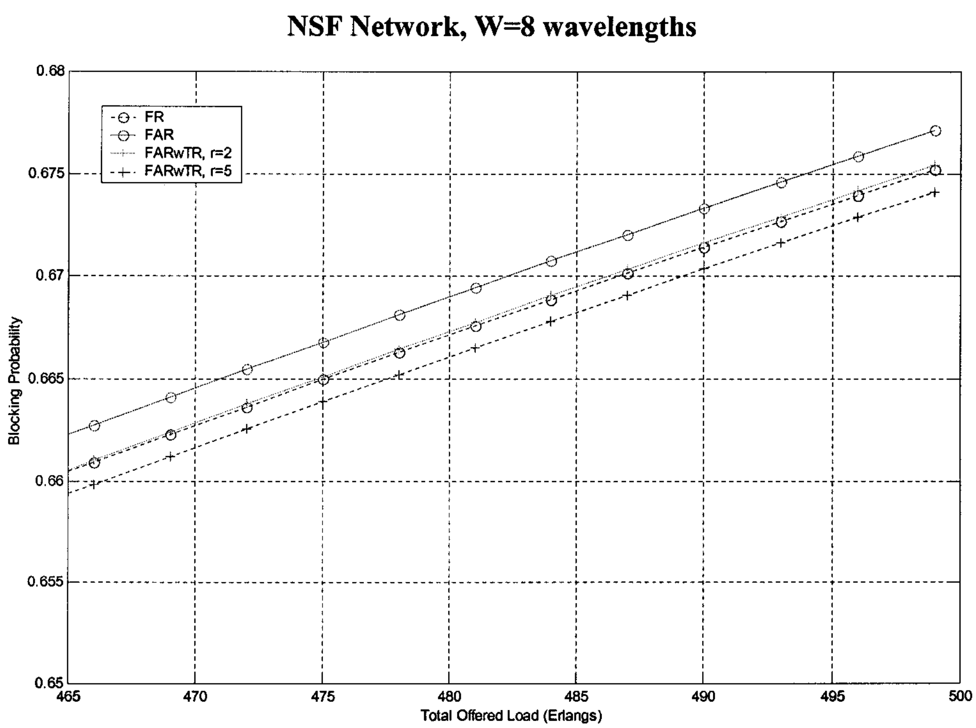

Figure 2.7: FAR with Trunk Reservation (FARwTR) - High Load

2.6 Conclusions

Real-time provisioning of optical channels has been presented in this chapter. Specifically, the work presented here has addressed provisioning of connections in a WDM-based network, which is defined as the process of dynamically selecting efficient end-to-end routes and assigning wavelengths, i.e., routing and wavelength assignment (*RWA*). We analytically modeled the *RWA* problem with different wavelength assignment schemes. The analytical model is based on the layered-graph approach; it models the arrival rate as a Poisson distribution and utilizes the moment matching techniques to model the overflow traffic between different wavelength layers and between alternate routes. Different routing algorithms were studied and the blocking probability performance was computed and compared with those that use heuristics. We have also proposed the trunk reservation technique to improve the blocking performance for the fixed alternate routing (*FAR*) and investigated its effect on heavy-loaded and light-loaded network. *FAR* with/without trunk reservation (*TR*) is one approach to improve the network performance; analytical models for alternate routing without trunk reservation are also presented. We validated the accuracy of the proposed models through numerical comparison with simulation results of the *RWA*. We also showed the efficiency of alternate routing in improving the performance. However, as the traffic load increases, alternate routing degrades the blocking performance and the improvement of *FAR* is very limited; this is due to the fact that alternate routing will occupy more transmission resources and thus, at higher loads will prevent direct traffic from being routed and leads to instability. By limiting the flow of the alternately routed traffic, one can overcome the instability problem. Trunk reservation (*TR*) is one technique to improve the performance of alternate routing at higher loads and can better manage the network resources by selecting the right trunk threshold.

Chapter 3

3. Unicast Traffic Grooming in IP/MPLS-over-WDM Networks

3.1 Introduction

The evolving next generation Internet transport infrastructure is moving towards a model of high-speed routers interconnected by intelligent, reconfigurable optical core networks that will directly provide a global transport infrastructure for legacy and new Internet Protocol (IP) services [1][2]. In this model, clients (e.g., IP/MPLS routers) are attached to an optical core network, and connected to their peers over dynamically switched lightpaths (logical connections) spanning potentially multiple optical cross-connects OXCs [3] (Figure 3.1). The optical core network consists of multiple optical cross-connects interconnected by optical links in a general mesh topology. This transition is driven by the deployment of high-speed IP routers and ATM/MPLS switches. Specifically, these data-centric network elements (NEs) provide the essential bandwidth management functions including multiplexing up to OC-12, OC-48, OC-192, GbE (Gigabit Ethernet), and 10GbE rates. The use of interfaces with such rates renders intermediate SONET/SDH multiplexing NEs as potentially obsolete. Reducing network overlay and eliminating SONET/SDH multiplexing and associated stand-alone NEs is also accompanied by removing SONET-layer traffic grooming and survivability functions and replacing them with management at higher (IP, ATM) or lower (WDM) layers. In this scenario, the function of multiplexing traffic onto wavelengths may be passed onto the IP/MPLS routers.

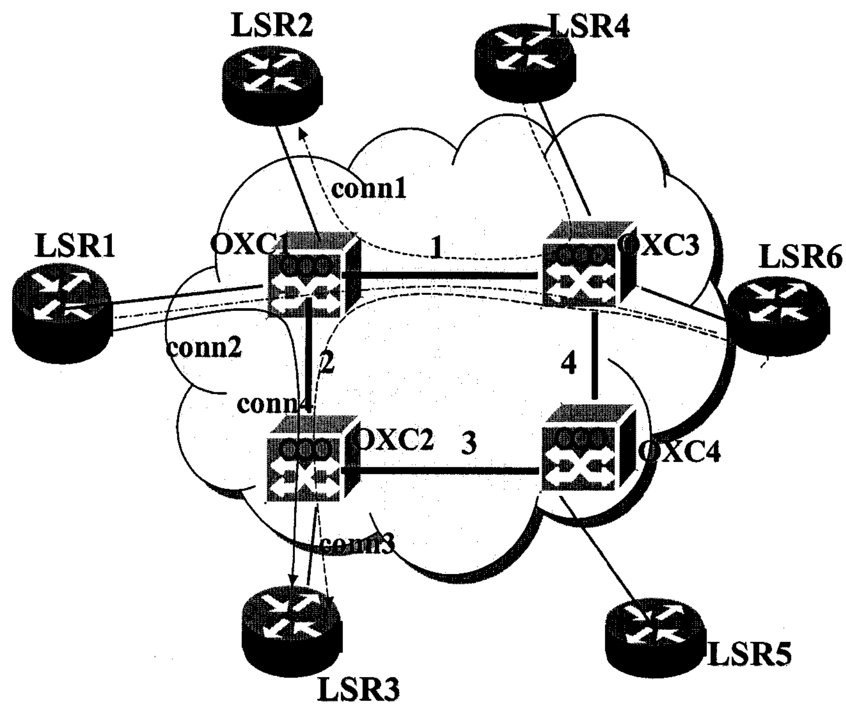

Figure 3.1: IP/MPLS-Over-WDM Network

In current network scenarios, the traffic is dynamic and heterogeneous where the networks are required to provide dynamic services to the user at a rate that is much lower than the full wavelength capacity. These sub-rate streams are very common and can comprise smaller TDM channels (e.g., SONET/SDH 155 Mb/s OC-3 or 622 Mb/s OC-12), or a variety of storage area network (SAN) protocol interfaces (e.g., 200 Mb/s Escon, 100/1000 Mb/s Ethernet, 1.0 Gb/s Fiber Channel, etc), or even arbitrary packet flows. In order to achieve maximum efficiency, one would need to bundle these low-rate traffic streams efficiently onto high capacity lightpaths so the number of wavelengths that have to be processed at each router is minimized. This is known in the literature as the traffic-grooming problem [4][5].

More recently, the problem of traffic grooming in WDM mesh networks has been addressed. For example, the authors of [4] investigate the problem of grooming lower-speed traffic streams into high capacity lightpaths in a WDM-based optical mesh network. A mathematical formulation is presented and several fast heuristics are proposed and evaluated. Meanwhile, in [5], the authors proposed two heuristics to route lower-speed traffic streams over a logical topology and derive analytical models for the network blocking probability. The performance of WDM networks with sparse and constrained grooming capabilities have also been studied in [6]. Here, the authors specify an analytical model to calculate the blocking performance based upon link and wavelength independence assumptions.

In this chapter, we propose new adaptive routing algorithms to dynamically route traffic flows over the logical topology and we compare their performance evaluations in term of call blocking rate with the conventional shortest path traffic-grooming algorithm approaches. The rest of this chapter is organized as follows. Section 3.2 describes the IP/MPLS over WDM network architecture; the traffic grooming algorithms are introduced in Section 3.3. Performance evaluation is presented in Section 3.4 and section 3.5 concludes the chapter.

3.2 IP-over-WDM Interconnection Models

The optical network model considered here consists of multiple Optical Cross-connects (OXCs) interconnected by optical links in an optical mesh network [4][7]. Each OXC is assumed to be capable of switching a data stream from a given input port to a given output port. This switching function is controlled by appropriately configuring a cross-connect table. A *lightpath* from an ingress port in an OXC to an egress port in a remote OXC is established by setting up suitable cross-connects in the ingress, the egress and a set of intermediate OXCs such that a continuous physical path exists from the ingress to the egress port. Even though the introduction of optical switches into the core network has alleviated electronic bottlenecks at intermediate routing nodes, appropriate wavelength routing algorithms are required to efficiently allocate channels for user requests. Assigning network resources to successfully carry connection requests (lightpaths) is well known as the routing and wavelength assignment problem (RWA) [8] and has been extensively studied over the past few years.

In this proposed network model, IP routers are attached to the optical core network and connected to their peers over dynamically switched lightpaths. Figure 3.2 shows the IP/MPLS over WDM node architecture for two wavelengths. The network node is composed of two parts: Wavelength routing switch (WRS) and IP/MPLS router. The WRS performs wavelength routing and enables space switching of wavelengths from one port to another. The IP/MPLS router is attached to the optical switch through an array of tunable transceivers (four transceivers in the example shown in Figure 3.2) and has its own instance of routing algorithm and helps on provisioning label switched paths (LSPs) and multiplex them efficiently into high capacity lightpaths and setting up new lightpaths to build adjacencies with other routers. With such an architecture, a signal is either switched from an input port to an output port without undergoing O/E/O (optical-electrical-optical) conversion, or converted into electrical at the local IP/MPLS router and dropped if this is the final destination or converted into electrical and statistically multiplexed with another traffic stream and sent out at the corresponding output port.

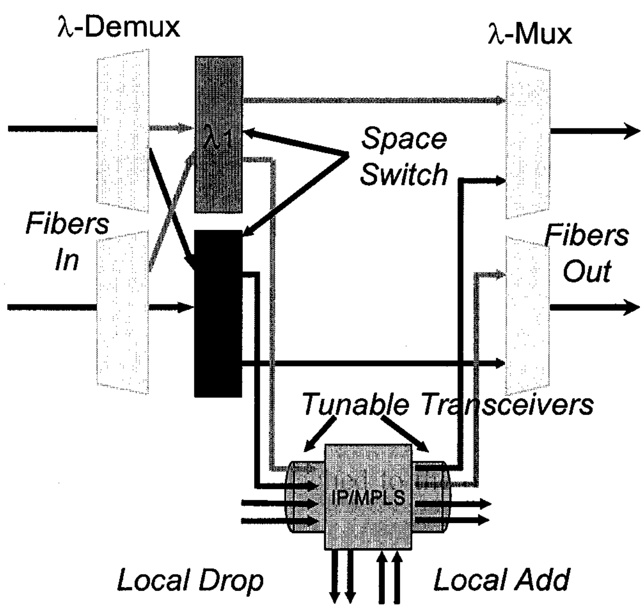

Figure 3.2: IP/MPLS-over-WDM Node Architecture

Here, the set of lightpaths connecting IP/MPLS routers represents the logical IP-connectivity between them. Based on this connectivity, IP routers are capable of configuring their routing tables, exchanging information regarding their connectivity, bandwidth usage of individual lightpaths, etc. This allows traffic-engineering procedures to be employed at the IP layer to effectively map the traffic into the corresponding lightpaths and load-balance the traffic across the network.

3.3 Traffic Grooming Algorithms

3.3.1 General Approach

To carry connection requests, lightpath connections may be established between pairs of nodes (IP routers, ATM switches, ADMs, etc.). A connection request may traverse a single-hop route or multi-hop route. In single-hop case, a connection is allowed to traverse a single lightpath (same wavelength is used throughout the entire route from source-to-destination), which means that only end-to-end traffic grooming (multiplexing) is allowed. In multi-hop case, a connection is allowed to traverse multiple lightpaths, i.e., a connection can be dropped/terminated at an intermediate node and multiplexed with other low-speed connections on different lightpaths (wavelengths) before it reaches its destination. In the case of a single-hop route, only calls with the same source-destination pair can be multiplexed onto one lightpath. Clearly, this will yield low lightpath utilization and further lower overall network throughput also. On the other hand, in the case of a multi-hop route, calls with different source-destination pairs can be multiplexed into the same lightpath.

We define a virtual topology, or simply, IP connectivity, to be the set of all lightpaths connecting edge IP routers amongst each other. We first start by initializing the virtual topology to empty and hence all IP routers' routing tables have no entries. Border routers supply large capacity and relatively aggregated flow to the optical domain. IP routers, based on their connectivity are capable of finding potential routes to carry the traffic streams by running their own instance of routing algorithm on the virtual topology (i.e. logical provisioning).

Specifically, the logical provisioning is achieved by considering established lightpaths as directional logical links that comprise the logical (virtual) topology. The logical topology construction is performed whenever a call is attempted to be served logically, since the topology changes every time a lightpath is set-up or torn-down. When the logical provisioning mechanism is invoked, the logical topology is checked for availability of a route spanning a single logical link (single-hop) or multiple logical links (multi-hops). Note that pruning is performed every time the mechanism is invoked. That is, logical links that do not have enough bandwidth to accommodate the call, or originate/terminate from/to a node whose IP module residual speed is not adequate to forward the call, are deleted from the topology.

This work assumes a dynamic routing and wavelength assignment algorithm that attempts to solve the routing problem and the wavelength assignment problem jointly by means of dynamic routing over multi-layered graphs where each layer represents a wavelength (RWA provisioning) [7]. This is achieved by associating each link in the network with a specific weight function that incorporates WDM specific information such as the number of available wavelengths and the total number of wavelengths. For simplicity we use a unit cost for all physical links (shortest path routing).

3.3.2 Logical-First Provisioning

In Logical-First scheme, depending on the algorithm to be used, if no available single/multi hop route were found on the logical topology, the source node sends a request to the ingress OXC to setup a lightpath on the physical topology, to the destination. Then, the ingress OXC invokes its routing and wavelength assignment (RWA) algorithm to setup a lightpath to the destination. Note that the OXC has to disseminate this information to other core OXC's and to the border IP router that is connected to it. Subsequently, the source IP router that had set up this lightpath adds an entry to its routing table that identifies this lightpath. It also maintains information about the bandwidth allocated along this lightpath. This information is then disseminated to other border routers through signaling channels.

3.3.3 Physical-First Provisioning

In Physical-First scheme, the physical layer is always attempted first to set up a new connection request. If the new lightpath is established successfully, a new logical/virtual IP/MPLS path is created in the logical (IP/MPLS) layer; this lightpath will be torn-down when it doesn't carry any more traffic. If the physical routing fails, then routing on logical topology is attempted which leads to multiplexing lower data rate (sub-lambdas) with other traffic streams on some existing lightpaths.

3.3.4 Traffic Grooming Routing Algorithms

We propose an adaptive routing algorithm to dynamically route traffic flows over the logical topology, where the resources are dynamically allocated (Dynamic Lightpath Establishments) as needed. Once the last call utilizing one or more lightpaths departs from the network, these lightpaths are torn-down as long as no other calls are utilizing them. Specifically, we propose dynamic *"Logical-First"* and *"Physical-First"* provisioning schemes. The new proposed dynamic schemes are compared with the conventional shortest path routing of the same grooming schemes.

- *Shortest Path:* This represents the base case, and it is used as a reference to evaluate, by comparison, the blocking performance of the proposed dynamic algorithms. In this scheme, we use two algorithms, the *"Logical-First"* approach and the *"Physical-First"* approach.
- *Dynamic Algorithm:* We propose an adaptive routing algorithm to dynamically route traffic flows over the logical topology, where the resources are dynamically allocated (Dynamic Lightpath Establishments) as needed. The logical link cost for the dynamic routing algorithm over the logical topology is based on the residual bandwidth of the link, and it is given by: $C_{ij} = \frac{1}{R_{BW,ij}}$, where $R_{BW,ij}$ =Residual Bandwidth on link *"ij"*. Note that if $R_{BW,ij}$ =Channel Capacity, then the logical link is released. Similarly to the used shortest path algorithms, we use two approaches for routing: The *"Logical-First"*, and the *"Physical-First"*.

We should note that the dynamic routing algorithms are not constraint to a fixed number of hops, contrarily to the single-hop routing, which always return a route of a single logical hop when found.

3.4 Performance Evaluation

The performance of the proposed routing algorithms is evaluated via simulation on a number of networks with various characteristics. As an example, simulations of the routing algorithm were run on the NSF network that consists of 14 nodes and 21 physical links. Adjacent nodes are connected via bi-directional physical links, where each physical link is assumed to carry 4 wavelengths. We use a dynamic traffic model in which call requests arrive at each node according to a Poisson process and an arrival session is equally likely to be destined to any node in the network. The wavelength channel capacity is assumed to be OC-192 (10 Gbps) and the sub-lambda requests are of OC-48 (2.45 Gbps). The edge routers are assumed to have enough interfaces and process all the traffic that can potentially pass through them. This assumption can be relaxed to account for the cases where routers have limited processing capabilities. The blocking probability is the metric used to evaluate the network performance. In each simulation run, a large number of requests are generated one after the other (30,000 requests), and the results are averaged over five simulation runs.

Figure 3.3 shows the blocking performance of the two proposed dynamic schemes versus the shortest path schemes. We observe that the probability for a connection to be routed using the *"Logical-First"* routing is relatively higher than the case of *"Physical-First"* routing in both cases of shortest routing and dynamic routing. This is due to the fact that the *"Physical-First"* algorithm attempts to increase the connectivity of the virtual topology as much as possible, thereby yielding more options for IP routing. From the same Figure, we can see the improvement in network performance introduced by applying dynamic routing. The dynamic *"Physical-First"* outperforms all other schemes. And this because the more the residual bandwidth, the less the cost of a logical link, hence connections tend to be routed on paths with the largest expected number of free trunks, which will distribute the traffic in the network.

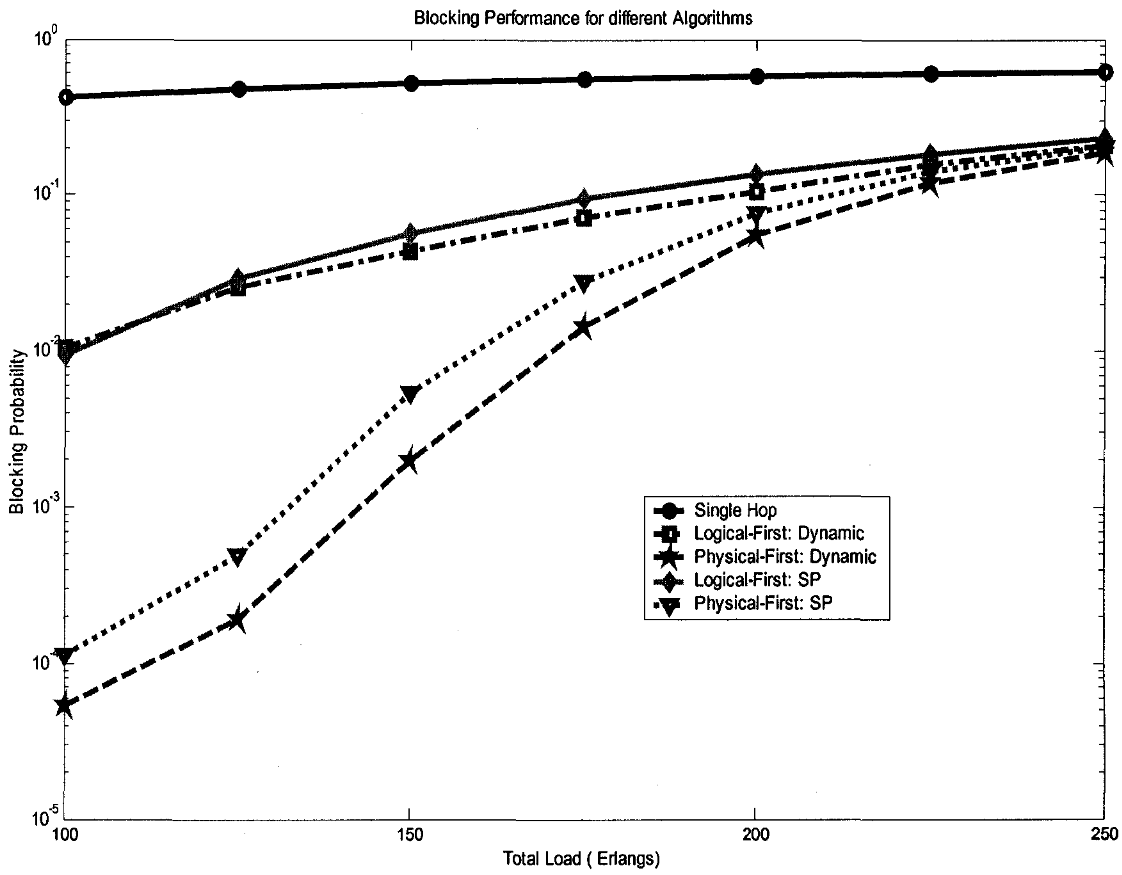

Figure 3.3: Comparison of the blocking performance of the different schemes

In Table 3.1, we see that, the dynamic *"Physical-First"* algorithm achieves higher connectivity than the shortest path *"Physical-First"* algorithm, and this is reflected by the higher percentage of logical routes used for provisioning (88%), and keeping at the same time a comparable percentage of physical routing (11%).

Actually, with more logical hops reserved for each connection, the residual bandwidths in the logical topology become less, and hence, less new connections will be served. This is confirmed via the simulation by a low performance for the *"Logical-First"* algorithm, where more than 90% of the routes were provisioned on the logical topology (Table 3.1). But that doesn't mean, the less the logical hops, the better the performance, otherwise the single-hop should perform the best, which is not the case at all, as it shows from Figure 3.3 that this scheme performs the worse. The fact is that, there is a compromise between the number of logical hops and the logical route cost, and both cases, *"Logical-First"* and *"single-Hop"* routing algorithms, don't provide such a compromise. An efficient dynamic algorithm should not span too many logical hops because this tends to reserve too many resources on the logical topology.

Table 3.1: Percentage of the used routes at load=150 Erlangs.

Scheme	**Physical Routes**	**Logical Routes**
Single Hop	24.3367%	23.2267%
Logical First: Dynamic	01.8400%	93.5700%
Physical First: Dynamic	11.3367%	88.4400%
Logical First: SP	03.4033%	90.7667%
Physical First: SP	19.1100%	80.3200%

From Table 3.1, we see that the dynamic *"Physical-First"* algorithm uses more logical routes than the shortest path *"Physical-First"* algorithm (8% more), but if we look at Figure 3.4, we can observe that the logical routes used in the dynamic *"Physical-First"* have less number of hops than the ones of the shortest path algorithm (logical hops formed of 3 hops in shortest path algorithm are more, however most of logical routes in both schemes are either formed of 2 or 3 hops). If we look at Figure 3.4, we see that the number of hops of the logical routes when using the *"Logical-First"* scheme are higher, we can see more logical routes consisting of more than 3 hops, and this is because when using the shortest path scheme, we always choose the shortest logical route, but by doing so, we might force new connection requests to be routed on much longer logical routes, especially when the logical routing is attempted first. In this case, the network connectivity is low, and the probability of having a long logical route is very high. When logical routing is attempted at high connected network, which is the case of the *"Physical-First"* scheme, it is more likely to find short logical routes, and hence at this point, the more used logical routes, the better the blocking performance (*"Physical-First"* routing). The overall results confirm that the dynamic *"Physical-First"* algorithm outperforms the others approaches for all the above-mentioned reasons.

3.5 Conclusions

This chapter has proposed new dynamic algorithms for efficiently routing (i.e., grooming) low-speed traffic streams over high capacity lightpaths in IP/MPLS over WDM networks. Specifically, we proposed adaptive routing algorithms to dynamically route traffic flows over the logical topology. We compared their performance evaluations in term of call blocking rate with the conventional shortest path traffic-grooming algorithm approaches. Using a simulation study, we showed that there is a compromise between the number of logical hops and the logical route cost. Our results showed that the proposed dynamic *"Physical-First"* routing provided such a compromise and outperformed all other schemes.

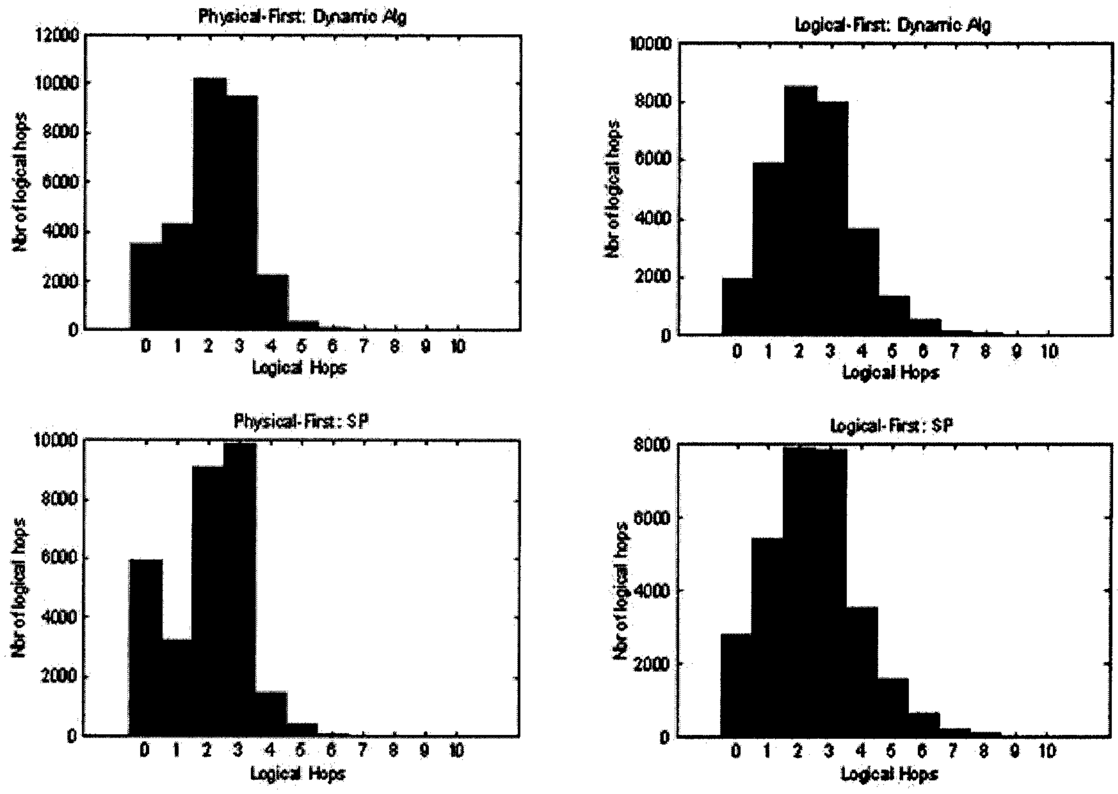

Figure 3.4: Number of logical hops of the different schemes at load=150 Erlangs

Chapter 4

4. Adaptive Integrated Routing Approach in Mesh-Based WDM Networks

4.1 Introduction

The phenomenal growth in Internet traffic, along with the abundance of bandwidth propelled by the explosion of wavelength-division multiplexing (WDM) has signaled the beginning of a new networking paradigm where the vision of integrating data networking and optical networking seems to be indispensable. It is widely accepted that the IP/MPLS-over-WDM networking architecture (the two-layer model) is the key to realizing such a vision where the WDM-based optical transport network (OTN) will directly provide a global transport infrastructure for legacy and new Internet protocol (IP) services [1][2]. In an IP/MPLS-over-WDM network, the OTN consists of multiple optical cross-connects (OXCs) interconnected via WDM links in a general mesh topology. Clients, e.g., IP/MPLS label switched routers (LSRs), are attached to the OXCs through wavelength ports and are connected to their peers over dynamically switched optical paths (lightpaths) spanning potentially multiple OXCs. An optical network cross-connect generically consists of an intelligent controller (OXC controller) and a cross-connect fabric. The interaction between the client and the OTN is over a well-defined signaling and routing interface, referred to as the User-Network Interface (UNI).

One of the critical issues facing the implementation of the two-layer model is how to provide the desired features of rapid provisioning and restoration between the optical and client layers. It is widely accepted that the best way to achieve this is to adapt the IP topology self-discovery and routing capabilities to the optical network environment. Multi-protocol label switching (MPLS) and its extension GMPLS (Generalized MPLS) have been proposed as the integrating structure between IP and optical layers [2][3][4]. Several organizations including the Optical Interworking Forum (OIF) and the Internet Engineering Task Force (IETF) have already proposed several architectural options on how IP routers must interact with the optical layer to achieve end-to-end connectivity, including overlay, augmented, and peer-to-peer interconnection models [2][3][4]. The simplest approach is to treat the optical layer completely separate from the IP layer (overlay model). In this model, the optical layer provides point-to-point connections (lightpaths) to the IP domain. The client routers request high-bandwidth connections from the optical network, via some UNI, and are provided with no knowledge of the optical network topology or resources. The resources managed by the optical layer include wavelengths and fibers on physical links. The IP/MPLS client layer manages bandwidth resources on lightpaths and routes traffic (label-switched paths (LSPs)) over the logical topology treating the lightpaths as links. A more sophisticated model that offers a tighter integration between IP and optical layers (peer-to-peer model) collapses the two layers into a single integrated layer managed and traffic engineered in a unified manner [5][6].

The overlay model is the most practical for near-term deployment because it is appropriate for the current telecommunications infrastructure that consists of multiple administrative domains. However, the simplicity of the overlay model comes at the expense of the inefficient use of network resources due to information hiding at the domain boundaries. Another serious limitation facing the overlay model is the large disparity between the coarse/fixed granularity bandwidth offered by the optical layer to clients (full wavelength level, e.g., OC-48 (2.5 Gbps), OC-192 (10 Gbps) and OC-768 (40 Gbps)) and the bandwidth requirement of a typical connection request, which is only a fraction a wavelength (e.g., STS-1 (51 Mbps), OC-3 (155 Mbps), OC-12 (622 Mbps), etc.). Thus, the optical layer can only provision connection requests that require a full wavelength capacity. Clearly, traffic demands with finer bandwidth granularity are the rule and those requiring full wavelength capacity are the exceptions. In addition, in networks of practical size, the number of source-destination traffic connections is still an order of magnitude higher than the number of available wavelengths. In fact, the inadequacy of the optical layer to support the diverse traffic granularity requirement is a serious limitation of the overlay model in particular and optical networking in general.

Unlike the overlay model, the peer-to-peer model (also referred to as the peer model) supports an integrated routing approach where the combined knowledge of resource and topology information at both the IP and optical layers are taken into account [5][6]. The unified IP/MPLS-based control plane in the peer model simplifies control coordination and fault handling among network elements with different technologies and allows for the efficient use of resources in a network composed of multiple technologies. The peer model does, however, present a scalability problem due to the amount of state and control information to be handled by any network element within an administrative domain. This means that a significant amount of state and control information must flow between the IP and optical layers, making the development of this model more time-consuming and complex. Compounding the problem is the fact that it is highly unlikely that a service provider who owns the OTN would ever give a client full access to the topology and resources of the optical network.

The rest of the chapter is organized as follows: Section 4.2 provides the motivations and proposed work. Sections 4.3 and 4.4 present an overview on previous work and the optical node architecture. Section 4.5 discusses the integrated routing approach and presents different dynamic cost functions. The performances of the different integrated approaches are evaluated and compared with sequential routing approaches in Section 4.6. Conclusions are presented in Section 4.7.

4.2 Motivations and Proposed Work

For the time being, adopting the overlay model seems to be the preferred choice for most of the carriers, though the inability of the model to adequately support the diverse traffic granularity requirement of the evolving data-centric networking paradigm remains a major open challenge that needs to be addressed. Compounding the problem is that the optical control plane of the overlay model as well as most of the GMPLS-based routing and signaling algorithms, which have been reported by the standards bodies and corresponding research activities, were developed to provision connection requests at the full wavelength capacity. To address the above limitations of the overlay model, we have proposed a novel, simple and scalable optical networking paradigm where most of the networking functionalities and intelligence have been shifted to the optical layer including supporting selective provisioning/restoration of diverse traffic granularities entirely on the optical layer's terms [7]. Specifically, in [7], a novel IP-over-WDM networking paradigm that uses the network resources as efficiently as the peer model to support provisioning of diverse traffic granularities, while still retaining the client/server relationship with the network (the customer has no network visibility and depends on network intelligence) and the simplicity of the optical UNI of the overlay architecture. Utilizing the proposed model, this work devises an adaptive integrated routing approach that takes into account the combined topology and resource usage information at both the IP and physical layers. Specifically, the proposed integrated routing uses a novel IP/MPLS-over-WDM networking paradigm that uses the network resources as efficiently as the peer model to support provisioning of diverse traffic granularities, while still retaining the client/server relationship with the network and the simplicity of the optical UNI of the overlay architecture.

4.3 Previous Work

In order to efficiently utilize the capacity of each wavelength channel (lightpath), several independent lower-speed traffic streams must be multiplexed into a single lightpath. The process of combining low-rate traffic streams onto high-capacity optical channels (lightpaths) is known in the literature as "traffic grooming" [8][9][10][11][12][13][14][15]. More recently, traffic grooming in mesh-based WDM networks has attracted an increased amount of research effort [8][9][10][11][12][13][14][15]. To support traffic grooming, two independent networking domains must be considered: the WDM-based optical network and the attached client networks [12]. The role of the optical network is to provide the clients with lightpaths (i.e. end-to-end connections that may span a number of physical links) at the full wavelength granularity. Client traffic, which has heterogeneous data rate of sub-wavelength granularity, is then transported over the set of these lightpaths (which provide a means of logical connectivity between distant client networks). Note that the logical topology is owned, controlled and managed by the clients (client layer).

Most of the research work that have addressed the traffic grooming problem in mesh optical networks uses the conventional sequential routing strategy to route a given connection request. Typically, four different operations are widely utilized to route a given connection request [11][12][13][14][15]: 1) Route the request over a single existing lightpath (Single-Hop routing); 2) Route the request over a multiple existing lightpaths (Multi-Hop routing); 3) route the request over a newly established lightpath (RWA problem); 4) Route the request over a combination of existing lightpaths and newly created lightpaths (hybrid approach) [14][15]. Different ordering of the four possible operations forms different grooming policies. The end result is that sequential routing is always used to serve the request and if all of the four ordered operations fail, then the request is blocked. Typically, routing at the IP layer is independent of routing at the optical layer and does not takes into account the combined topology and resource usage information at both the IP and optical layers. Hence the selected route is always sub-optimal.

Our proposed routing strategy, however, is a truly integrated routing approach that takes into account the combined topology and resource usage information at the IP (access) and optical layers. A truly integrated routing approach requires two components. The first component is to devise a practical technique in which every node in the network is capable of maintaining a single topology and resource usage database for both the client and optical layers to support an integrated routing. The second crucial component is to assign a dynamic uniform cost across the logical and physical links, which is then used by the routing algorithm to adaptively select a route. Thus, the real challenge in implementing an integrated routing approach is how to assign a dynamic cost, which maximizes the network resources utilization across both the logical and physical layers.

4.4 Optical Node Architecture

To support traffic grooming, the cross-connect fabric of each optical node should have the capability of switching traffic at the wavelength granularity as well as at finer granularities [10][15]. Therefore, a hybrid switching solution that capitalizes on existing electronic switch fabrics as well as all-optical switch fabrics by making use of each switch's functionality and capability, appears to be the most appropriate for building the optical nodes of the proposed model.

The proposed integrated routing approach utilizes our optical layer-based unified control plane where the node architecture is composed of three components (Figure 4.1): (1) an all-optical switch fabric; (2) an electronic switch fabric; and (3) a non-traffic bearing OXC controller module [7]. The all-optical switch fabric performs pure optical switching without wavelength conversion capabilities and the granularity of switching is the entire wavelength. The electronic switch fabric is a high-speed switch fabric capable of multiplexing, demultiplexing, and switching low-speed traffic streams up-to the wavelength capacity. The electronic switch fabric is attached to the all-optical switch fabric through an array of transceivers and can generate and terminate the traffic to/from a lightpath. The number of wavelength channels that can be terminated/generated into/from the electronic switch is a function of the transceiver array size.

Under this scenario, each OXC controller is assumed to maintain a single topology and resource usage database for both the client and optical layers. The OXC controller is now responsible for creating, maintaining and updating both the physical and logical connectivity tables. Thus, the OXC provisions on-demand lightpaths (full-lambdas) as well as low-speed connection requests (sub-lambdas). The responsibility of the edge router (client LSR) is then simply to request a service from the OTN (both full-lambdas and sub-lambdas) and the latter is responsible for providing this service.

Using this integrated routing approach, the combined knowledge of resource and topology information at both the IP and optical layers are taken into account. Note, however, that this approach is different from the peer model and the integrated approaches proposed in [5][6]. In those schemes the integrated routing approach is achieved through the exchange of a significant amount of state and control information between the IP and optical layers. This renders their implementations more time consuming and complex and raises the well-known scalability problem. The proposed integrated routing approach requires no exchange of information between the boundaries of the two layers except for that of the simple UNI. Furthermore, and since the optical layer is now aware of both the logical and physical topologies and connectivity, it is now able to service calls by selecting a mixture of existing (logical routing) and setting up new lightpaths (RWA) in a way that optimizes resource usage. This introduces the important concept of hybrid provisioning.

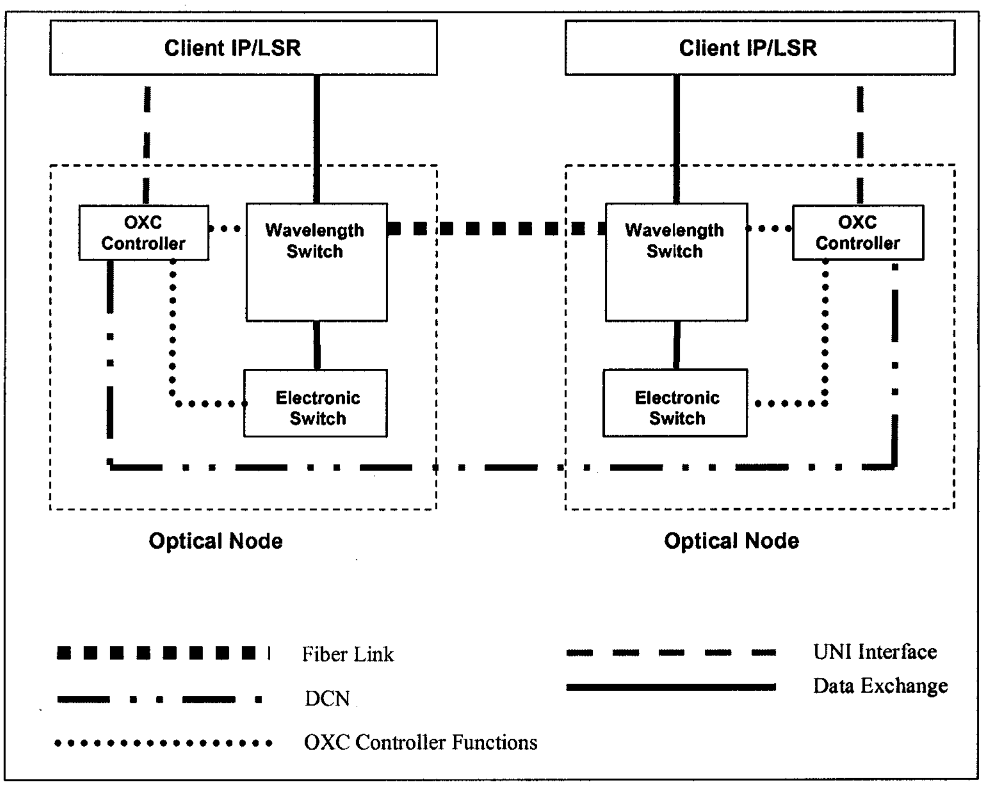

Figure 4.1: Optical node architecture

4.5 The Integrated Routing Approach

The network is modeled as an integrated directed layered-graph where each layer represents a wavelength [16][17]. On the integrated layered-graph, an established lightpath on wavelength *"i"* between a pair of ingress-egress nodes is modeled by a *directed link (dashed)* that connects these nodes. Once the directed link is created/added, the corresponding physical links connecting the same ingress-egress pair on layer *"i"* are removed from the original graph. Thus, a *directed link* in the integrated layered-graph represents a *logical link or a lightpath* in the IP/MPLS layer while *an undirected link (solid)* represents a *physical link* in the physical layer. As an illustrative example, Figure 4.2 shows a 4-node network with two wavelengths per fiber. The network is modeled as two layers, each corresponding to a wavelength, λ_1 and λ_2, respectively. Initially, the topology at each layer resembles the physical network. Assume that a request of bandwidth "*m*" ($m < W$; *W* is the full wavelength capacity) is to be routed from node *A* to node *C* on λ_1. The remaining bandwidth (W-m) is modeled by establishing a cut-through path at *"layer 1"* between the routers attached to nodes *A* and *C*. Once the lightpath (logical link) is established on λ_1, the corresponding physical links on *"layer 1"*, *AB* and *BC*, are eliminated. Note that all other layers must also be aware of this lightpath (via the OXC controller's database). If the remaining capacity on logical link *AC* reaches *W* after a disconnection event, then the logical link is eliminated and the original physical links that constituted the logical *AC* link (*AB* and *BC*) are re-established with the full channel capacity. As an example, assume after the release of a previously established connection, the resources on some links become free (the whole bandwidth is not used anymore), which leads to an un-used lightpath. Therefore, and since we are using a dynamic provisioning approach, this lightpath has to be torn down to release the resources and the logical link will be replaced by physical links in the integrated graph.

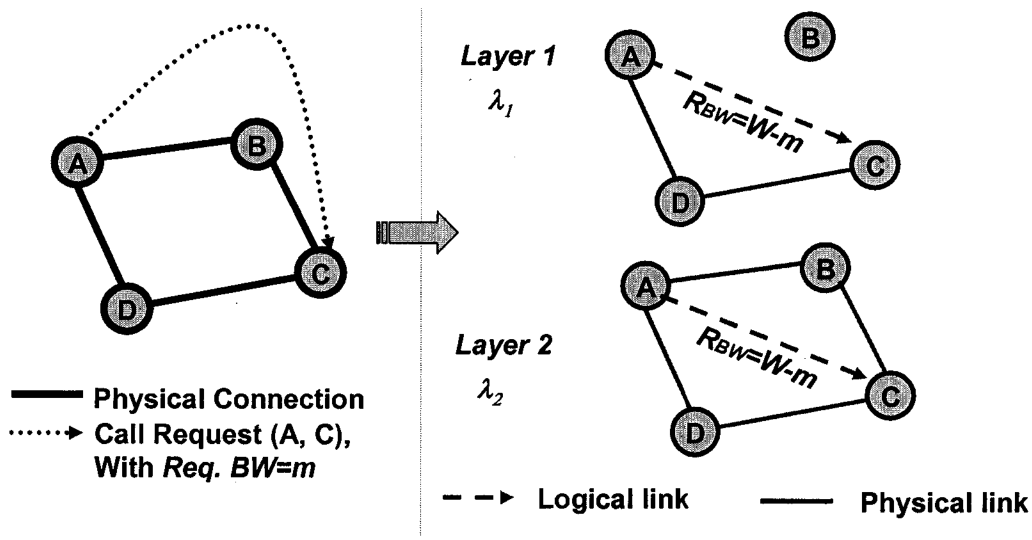

Figure 4.2: Integrated layered-graph representation

4.5.1 Integrated Routing Algorithm

Each link in the integrated graph (both logical and physical) is assigned a cost to reflect the weight of that link. The link cost can be a function of a number of metrics such as number of hops, residual link bandwidth, router interface capacities, the number of O-E-O conversions, etc. After a cost is assigned to each link, our proposed integrated routing algorithm uses the simple minimum path computation (Dijkstra's algorithm) to calculate the explicit route. As an example, if the cost function represents the number of hopes, Dijkstra algorithm computes the shortest path from the source to the destination. The minimum cost path is computed taking into account both the logical and the physical links. Thus, a selected path may use an existing lightpath (logical routing), set up a new lightpath (routing and wavelength assignment (RWA)), or use a mixture of existing and new lightpaths (hybrid approach) in a way that optimizes resource usage. The challenge is how to assign a uniform cost across both the logical and physical links. In general, the total cost of a path, C_{path}, is defined as

$$C_{path} = \sum_{\substack{l_i \in I \\ l_j \in J}} (C_{phys,l_i} + C_{\log,l_j}) \tag{4.1}$$

Where I and J are the set of all physical and logical links included in the path between ingress-egress pair respectively, C_{phys,l_i} is the cost of the physical link l_i, and $C_{\log,l_j}$ is the cost of the logical link l_j. Once the weights of all links (logical and physical) are assigned, minimum cost routing is performed and the cheapest route is selected. Note that the routing algorithm only considers the first available route between the ingress-egress pairs, but pruning is used, which means once the route is found we can guarantee that there are available resources to serve the call. If no route is found, the call is blocked.

4.5.2 Link Cost Functions

In this section, we will develop two different cost metrics and examine the tradeoffs between them to decide on an optimum or near-optimum routing. The first cost metric favors routing connections on the least loaded lightpaths while the second cost metric favors routing connections on the most loaded lightpaths [18].

4.5.2.1 Cost Metric Type 1

Assume that the link cost metric will be assigned such that the connection requests will be routed on those links (both logical and physical) with the highest residual (available) bandwidth capacities. One way to do that is to define the cost of the links as follows

$$\underline{\text{Physical link cost:}}\ C^{\lambda}_{phy,li} = \begin{cases} \frac{1}{W} & \text{available wavelength on layer } (\lambda) \\ \infty & \text{used wavelength on layer } (\lambda) \end{cases} \tag{4.2}$$

$$\underline{\text{Logical link cost:}}\ C_{\log,lj} = \begin{cases} \frac{1}{R_{BW,lj}} & 0 < R_{BW,lj} < W \\ \infty & R_{BW,lj} = 0;\ R_{BW,lj} = W \end{cases} \tag{4.3}$$

$R_{BW,lj}$=residual bandwidth on the link l_j. Note that, if $R_{BW,lj} = W$, then the logical link is released.

Using the link cost defined in (4.2) and (4.3), the routing algorithm is always constrained to favor physical links over logical links when both are available (W is always greater than R_{BW}). As an example, if there is a connection request from A to D and there is a logical link connection from A to D with a residual bandwidth of 2.5Gbps, the cost of this link will be $C_{\log} = \frac{1}{2.5} = 0.4$ (according to (4.3)). On the other hand, the cost of the physical link (A, D), using another layer/wavelength, will be $C_{phys} = \frac{1}{10} = 0.1$ (wavelength capacity is assumed 10Gbps). Therefore, the routing algorithm favors the physical link on the logical link. This is a special case of the sequential routing approach used in [11], where the algorithm routes connection requests on the physical layer first and only when it fails, it tries routing on the logical layer. Note that the difference, however, is that our approach is an integrated approach, hence it can route new connections on a lightpath sequence - like a multi-hop path on the logical topology - except that it may contain lightpaths which do not exist and need to be set-up. To address the problem of favoring always the physical links, we redefine the cost of a physical link as follow

$$C^{\lambda}_{phy,li} = \begin{cases} \frac{K}{W} & \text{available wavelength on layer } (\lambda) \\ \infty & \text{used wavelength on layer } (\lambda) \end{cases} \tag{4.4}$$

K is a varying optimization parameter and needs to be calculated. The problem then is to calculate the value of K that optimizes the cost of the physical links and consequently optimizes the overall path cost by minimizing the total blocking probability. The idea is not to constraint the order of the search (i.e., the order of routing in terms of order of logical routing, physical routing or a combination of both), but rather the order is decided by the algorithm such that the blocking probability is minimized. In this case, (4.1) can be rewritten as:

$$C_{path} = |I| \times \frac{K}{W} + \sum_{l_j \in J} \frac{1}{R_{BW,lj}} \tag{4.5}$$

Where, $|I|$ is the cardinality of the set of all the physical links included in the path.

Let us first start with the two extreme values of K. For instance, if K=0, the cost of any physical link is zero, and hence the cost of a newly created lightpath is always less than that of an existing lightpath. This means that the algorithm will always favors physical routing before logical routing, and the routing algorithm becomes similar to the sequential physical first routing [11]. On the other hand, when K is large enough (e.g., K=10), the cost of the logical link is less than that of the physical link. This means that the algorithm will favor logical routing over physical routing, and the integrated model again becomes similar to that of the sequential routing approach with logical routing first [11]. Between these two extreme cases, there are some values of K that will optimize the cost of the physical links and consequently the total cost of the path, in order to minimize the path/network blocking probability.

4.5.2.2 Cost Metric Type 2

This case assumes that the link cost metric will be assigned such that connection requests will be routed on those logical links with the lowest residual (available) bandwidth capacities (most-loaded lightpaths). One way to do that is to define the cost of the links as follows

Physical link cost: $$C^{\lambda}_{phy,li} = \begin{cases} \alpha & \text{available wavelength on layer } (\lambda) \\ \infty & \text{used wavelength on layer } (\lambda) \end{cases} \tag{4.6}$$

Logical link cost: $$C_{\log,lj} = \begin{cases} \beta \dfrac{R_{BW,lj}}{W} & 0 < R_{BW,lj} < W \\ \infty & R_{BW,lj} = 0; \quad R_{BW,lj} = W \end{cases} \tag{4.7}$$

Where α is the basic physical cost, β is an optimization parameter to be determined, and $\frac{R_{BW,lj}}{W}$ is the normalized residual bandwidth of the logical link l_j. Note that if $R_{BW,lj} = W$, then the cost of logical link becomes β and the logical link will be reduced to a physical link; therefore it is more appropriate to consider $\beta=\alpha$. That means the logical link cost is always less than the physical link cost, ($\frac{R_{BW}}{W} < 1 \Rightarrow \beta \frac{R_{BW}}{W} < \beta$), hence using an existing lightpath is cheaper/better than setting up a new connection on the same link. In other words, this cost function maximizes the usage of the existing lightpaths. This will keep light-loaded lightpaths unused to accommodate future connections that might arrive with higher bandwidth requests, leading to a lower blocking probability. In this case, (4.1), can be rewritten as

$$C_{path} = |I| \times \beta + \sum_{l_j \in J} \beta \frac{R_{BW,lj}}{W} \tag{4.8}$$

Where, $|l|$ is the cardinality of the set of all the physical links included in the path.

The value of β that optimizes the total path cost, i.e., minimizes the blocking probability, is obtained through simulation by calculating the total blocking probability of the network for different values of β ranging from a minimum value to a maximum value. Note that, changing the value of β doesn't change the order of provisioning (physical first or logical first), β only represents the base cost of a physical link.

4.6 Performance Evaluation

The performance of the proposed integrated routing algorithm is evaluated via simulating several network topologies that demonstrated similar conclusions. In this chapter we present results for the 14 nodes, 21-physical links NSF Network. Adjacent nodes are connected via bi-directional physical links, where each physical link is assumed to carry 4 wavelengths.

The simulation results are based on the following assumptions:

- Dynamic traffic model is assumed. Call requests arrive at each node according to a Poisson process with a network arrival rate λ. An arrival session is equally likely to be destined to any node in the network. The session holding time is assumed to be exponentially distributed with mean $1/\mu$.
- The wavelength channel capacity is assumed to be 10 Gbps, and the sub-lambda requests are uniformly distributed in the interval (0, 10] Gbps.

- The electronic switches are assumed to have enough interfaces (transceiver array) and process all the traffic that can potentially pass through them.
- All OXC's are assumed to have no wavelength conversion capabilities.

4.6.1 Heuristics

4.6.1.1 Integrated Routing (IR)

Using the cost functions defined in 4.5.2.1, i.e., "Type 1" and in 4.5.2.2, i.e., "Type 2", we define the integrated routing heuristics Type1-IR and Type2-IR respectively. Then we compare Type1-IR and Type2-IR with the conventional sequential routing approaches, namely, Physical First Routing (PF) and Logical First Routing (LF).

4.6.1.2 Physical First (PF)

The routing algorithm is invoked first on the physical layer and only when it fails it is invoked on the logical layer. For comparison purposes, we use Type 1 and Type 2 cost functions to define the PF sequential routing algorithms (Type1-PF) and (Type2-PF) respectively.

4.6.1.3 Logical First (LF)

The routing algorithm is invoked on the logical layer first and then when it fails it is invoked on the physical layer. For comparison purposes, we use Type 1 and Type 2 cost functions to define the LF sequential routing algorithms (Type1-LF) and (Type2-LF) respectively.

4.6.2 Performance Results

The blocking probability is the metric used to evaluate the network performance. In each simulation run, 30,000 requests are generated one after the other, and the results are averaged over 5 simulation runs.

Figure 4.3 (a) and Figure 4.3 (b) show the blocking probability over a wide range of (K, β) values for three different network loads using "Type1-IR" and "Type 2-IR" algorithms respectively. As expected, and as can be seen from the figures, there exist a range of K (2-4) and β (1- 2.5) values that minimize the blocking probability. K=2.5 and $\beta = 1$ are chosen as the optimum values since they correspond to the minimum blocking probability.

Figure 4.4 compares the performance of the proposed integrated routing algorithms (using the calculated optimum values for K and β) with the conventional overlay routing (sequential) approaches using the same cost functions defined in Type 1 and Type 2. As expected, both integrated routing algorithms outperform the sequential routing approaches. Note that, in the case of the sequential routing, routing on the physical layer first scheme outperforms routing on the logical layer first scheme, which is consistent with the results of [11].

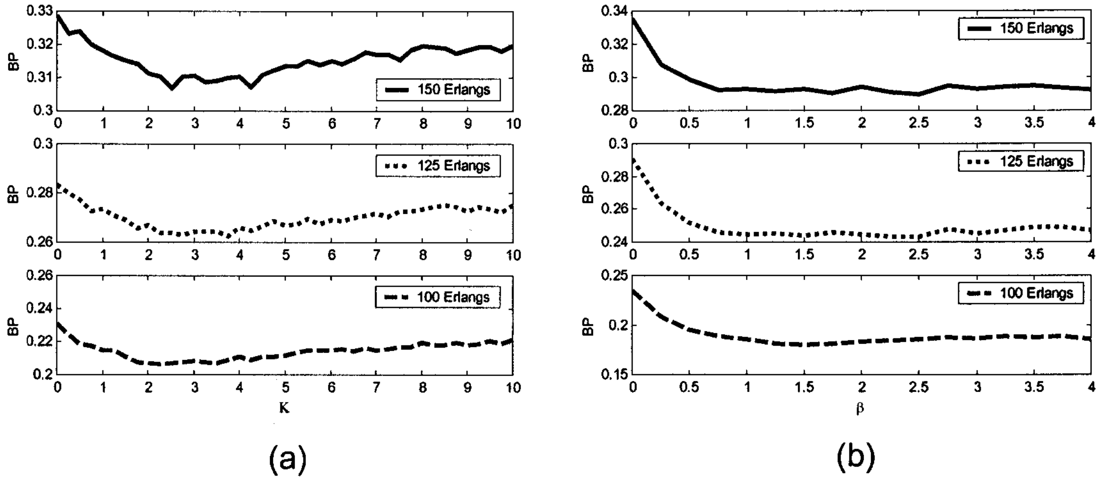

Figure 4.3: Optimization of the tradeoff parameters.

(a) Blocking probability as a function of K using Type1-IR algorithm. (b) Blocking Probability as a Function of β using Type2-IR algorithm

It can also be seen from Figure 4.4 that the performance of the routing algorithm that uses Type-2 link cost function always outperforms that of Type-1. Note that this is true for both the sequential and integrated routing. Hence, this indicates that using a cost function that maximizes the usage of the existing lightpaths will always yield better performance. This can be explained by inspecting Table 4.1, which classifies the percentage of call-provisioning for both the sequential and proposed integrated routing algorithms, according to the routing topology used (e.g., logical, physical, hybrid). We can see clearly that the hybrid provisioning of the integrated routing algorithms is achieved at the expense of the pure physical provisioning. Therefore, the percentage of pure physical provisioning is reduced compared to that of the sequential routing approaches. Thus, reducing pure physical provisioning (setting up fewer new lightpaths) can be taken as a first general guideline for improving the routing performance. Note also, as can be seen from Table 4.1, that the reduction of pure physical routing, for all Type-2 routing algorithms (IR, LF, and PF), is also associated with an increase in pure logical routing. Thus, a link cost function that can support the unique combination of minimizing pure physical provisioning and at the same time maximizing logical provisioning will always yield better routing performance.

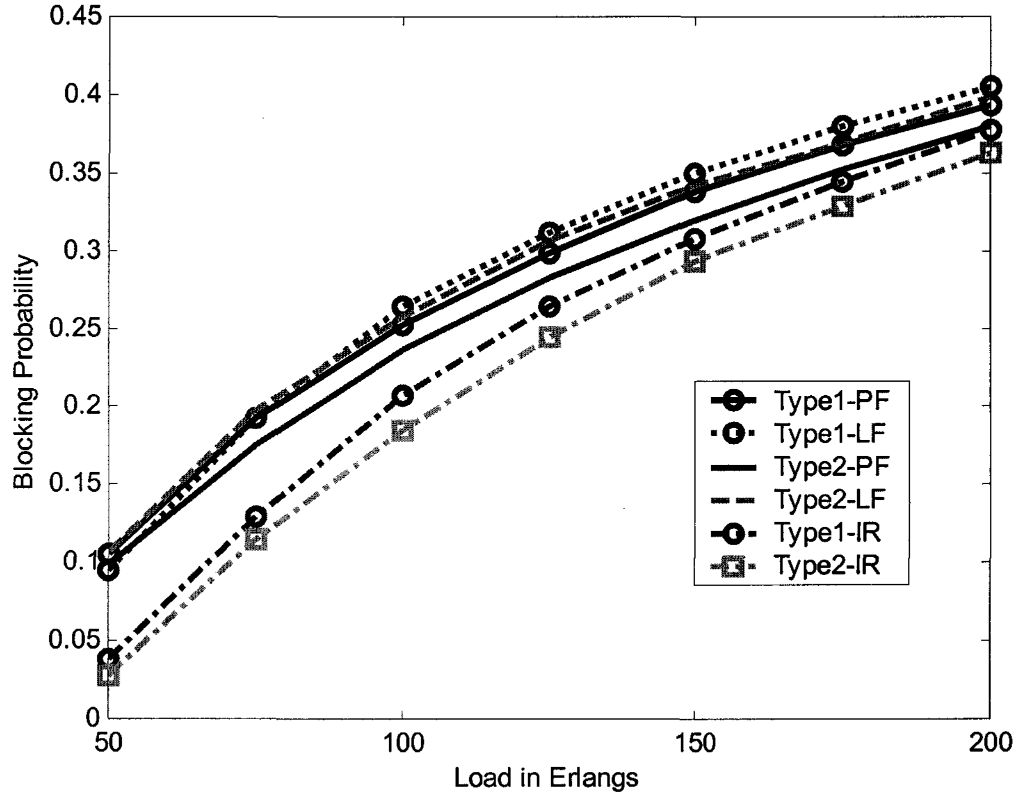

Figure 4.4: Performance evaluation of the different algorithms

Table 4.1: Percentage of call provisioning (NSF NET, 4 wavelengths, 150 Erlangs)

Scheme	**Physical Provisioning**	**Logical Provisioning**	**Hybrid Provisioning**
Type1-IR	9.93 %	41.66 %	19.62 %
Type2-IR	7.58 %	48.27 %	15.85 %
Type1-PF	22.58 %	44.51 %	0 %
Type1-LF	17.20 %	48.89 %	0 %
Type2-PF	20.73 %	48.65 %	0 %
Type2-LF	15.03 %	52.61 %	0 %

4.7 Conclusions

This chapter has proposed and developed an adaptive integrated routing approach that takes into account the combined topology and resource usage information at both the IP and optical layers. Two different cost metrics have been developed and used to examine the performance of the proposed integrated routing approach. We have introduced tradeoff parameters to optimize the cost of logical and physical links in the network. This optimization technique, which has never been addressed in any previous work, allowed us to choose a dynamic cost function to efficiently use the network resources and obtain a near-optimal integrated routing. Instead of using an obvious/static cost function, we optimized the cost of the logical and physical links through simulation. This technique "guaranteed" an optimized route that uses efficiently the network resources under consideration without worrying about assuming "grooming policies" to efficiently use the network resources. Simulation results have shown that the proposed simple and scalable integrated routing approach outperforms the overlay sequential routing approaches. Furthermore, it has been shown that the link cost function (i.e., cost function Type 2) that minimizes pure physical provisioning and at the same time, maximizes logical provisioning, will always yield better routing performance. Finally, it is important to emphasize that other crucial performance metrics such as differentiated restoration algorithms and associated signaling protocols are beyond the scope of this thesis.

Chapter 5

5. Dynamic Provisioning of Low-Speed Unicast and Multicast Traffic in Mesh-Based WDM Networks

5.1 Introduction

The abundance of bandwidth propelled by the explosion of wavelength-division multiplexing (WDM) along with recent advances in optical networking technology has successfully provided the required capacity to meet the phenomenal growth in Internet traffic. Commercially available WDM transmission systems can support greater than 1 Tbps over a single fiber by means of multiplexing more than a hundred channels at 10 Gbps each [1]. In a wavelength-routed network, data are transported in all-optical WDM channels (lightpaths) where the bandwidth granularity is at the full wavelength level. A lightpath is an end-to-end connection that may spans a number of physical links. If no wavelength converters are used, a lightpath is associated with the same wavelength on all physical links spanning the entire path from source-to-destination (wavelength continuity constraint). The set of established lightpaths forms the logical topology of a WDM network. Data can be processed electronically (added /terminated) only at the endpoints of a lightpath, and switched optically (cut through) at intermediate nodes of the underlying physical topology.

A major shortcoming in current WDM networks is the large disparity between the coarse/fixed granularity bandwidth offered by the optical layer to clients (full wavelength level, e.g., OC-48 (2.5 Gbps), OC-192 (10 Gbps) and OC-768 (40 Gbps)) and the bandwidth requirement of a typical connection request, which is only a fraction of a wavelength (e.g., STS-1 (51 Mbps), OC-3 (155 Mbps), OC-12 (622 Mbps), etc.). Clearly, traffic demands with finer bandwidth granularity are the rule and those requiring full wavelength capacity are the exceptions. In addition, in networks of practical size, the number of source-destination traffic connections is still an order of magnitude higher than the number of available wavelengths.

In order to efficiently utilize the capacity of each wavelength channel (lightpath), several independent lower-speed traffic streams must be multiplexed onto a single lightpath. The process of combining low-rate traffic streams onto high-capacity optical channels (lightpaths) is known in the literature as "traffic grooming" [2][3]. To support traffic grooming, the cross-connect fabric of each optical node should have the capability of switching traffic at the wavelength granularity as well as at finer granularities [2][3].

Most early work on traffic grooming has focused on SONET rings, where traffic is often static and known in advance [3][4][5][6]. More recently, traffic grooming in mesh-based WDM networks has attracted an increased amount of research effort [7][8][9][10][11]. Most of these studies have assumed only unicast traffic. However, as networks evolve to support more bandwidth-intensive applications, and as rich multimedia and real-time services become more popular, next generation networks are expected to support both unicast and multicast applications (e.g., multiparty conferencing, software and video distribution, and distributed computing, etc.). To support multicasting at the physical layer of WDM networks, the concept of a light-tree has been introduced [12][13][14][15][16][17][18][19]. A light-tree is a point-to-multipoint extension of a lightpath, where the branching nodes of a light-tree are equipped with optical power splitters.

Similar to the case of unicast traffic demands, some of these multicast applications require only a fraction of the channel capacity (for example, HDTV needs only 20 Mbps). Thus, dedicating an entire light-tree to a single or few users may lead to a huge waste of network resources. To improve the network throughput, one would need to bundle several low-rate unicast and multicast traffic streams efficiently onto a single high capacity light-tree so that the number of wavelengths that have to be processed at each node is minimized. Hence, the problem of multicast traffic grooming is expected to become an important area for future research work. Furthermore, as network architectures transition from ring-based to mesh-based, both unicast and multicast traffic grooming in mesh-based networks will become an important extension to current ring-based grooming algorithms.

Although the problem of all-optical multicasting has received considerable attention in the literature [12][13][14][15][16], the problem of grooming multicast traffic has received little attention and has only considered static multicast traffic [20][21]. This chapter addresses the problem of dynamically provisioning low-speed unicast and multicast connection requests in mesh-based WDM optical networks. Specifically, this work focuses on building a dynamic logical topology where lightpaths/light-trees are setup and torn down in response to dynamic multicast traffic demands. We develop several routing/provisioning schemes to dynamically provision low-speed unicast and multicast connection requests. A constraint-based grooming strategy is devised to utilize the overall network resources as efficiently as possible by selecting the most appropriate combination(s) of the existing multiple routing/provisioning schemes. Based on this strategy, several different sequential multicast grooming heuristics are first presented. Then, we devise a hybrid grooming approach and combine it with sequential approaches to achieve a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches.

To achieve our objective, we decompose the problem into four sub-problems: 1) Routing problem. 2) Design of a light-tree based logical topology. 3) Provisioning problem. 4) Traffic-grooming problem. The simulation results of the proposed schemes are compared with each other and with those of conventional non-grooming approaches.

The rest of this chapter is organized as follows. Section 5.2 presents a background and an overview of multicasting problem in WDM networks along with a review of related work. Section 5.3 presents the network model and Section 5.4 presents multicast routing and wavelength assignment. Section 5.5 outlines the principles for designing a hypergraph logical topology used for creating multicast trees. Different multicast grooming methodologies and algorithms as well as the used heuristics are presented in Section 5.6. Performance evaluation is presented in Section 5.7 and the chapter concludes in Section 5.8.

5.2 Background and Overview

5.2.1 Multicasting in WDM Networks

Multicasting is the ability to transmit a message from a single source node to multiple destination nodes. Multicasting has emerged as one of the essential features in current and future networks with the development of computer and communication applications such as distributed computing, audio and video conferencing, software and video distribution, and database replication.

The simplest approach to serve multicast traffic is to treat every multicast request as a set of separate unicast requests and route each request independently. This approach, however, results in a huge waste of network resources. Hence, efficient multicast approaches should be applied to satisfy near optimal usage of the various network resources (i.e., link bandwidth, number of receivers, etc.). Using these multicast schemes, information is transmitted along a set of physical links, which constitute a multicast tree.

Multicasting is attractive in WDM networks, as with the inherent light splitting capability of some optical switches, it is more efficient to perform light splitting than copying IP datagrams in electronics. Furthermore, performing multicast in optics provides consistent support of format and bit-rate transparencies across both unicast and multicast transmissions [13][14]. Multicast routing in all-optical wavelength-routed networks implies that given the network topology along with limited network resources, the objective is to construct a multicast tree (light-tree) from the source to the destination nodes in order to lower the blocking probability and reduce the number of electronic components [12][13][14][15][16][17][18][19]. A light-tree is an all-optical point-to-multipoint virtual connection in which the source of a light-tree transmits the data on a particular wavelength, and the data reaches all the destination nodes through the use of optical splitters that can split the optical signal from a single incoming port to multiple outgoing ports [16]. Therefore, using these splitters, an optical signal can be delivered to multiple destinations along a set of physical links, which constitute a multicast tree with the source node as the root.

5.2.2 Review of Related Work

The problem of grooming multicast traffic in optical networks is an important problem that has received little attention given its immense practical importance [20][21]. In [20] the authors proposed an ILP formulation in order to minimize the number of wavelength channels used and the cost of the network in terms of the number of SONET Add/Drop Multiplexers (ADMs). In that work, the network was represented as three different levels, namely the physical, the lightpath and the connection level. The authors considered non-uniform static traffic; they also introduced heuristics to solve the problem by obtaining first an initial solution using shortest path tree and first-fit wavelength assignment, and then iteratively improving it by exploring other routes. The authors in [21] formulated an optimization problem for the design of a light-tree based logical topology. That problem consisted of two sub-problems, namely the multicast routing and wavelength assignment, and the design of a light-tree based logical topology for multicast streams. In that work, ILP formulation was used for the design of optimum light-trees and then the light-tree based logical topology was modeled as a hypergraph over which static multicast streams were routed. To the best of our knowledge, the problem of grooming dynamic multicast traffic and designing a light-tree based hypergraph logical topology for dynamic multicast traffic in WDM networks has not been previously considered.

5.3 Network Model

We consider a WDM network with n optical nodes interconnected by bi-directional fiber links, where each link carries w wavelengths and each node is equipped with a multicast-capable all-optical switch (MC-OSW) with p input ports (fibers) and p output ports. The multicast capability is supported via optical splitter banks, where a $p \times p$ optical splitter bank splits the input signal into p identical output signals [16]. Note that splitter banks may be enhanced to compensate for the power loss, wavelength conversion, and signal regeneration. A $p \times p$ MC-OSW that supports w wavelengths consists of p ($1 \times w$) demultiplexers, p ($w \times 1$) multiplexers, w splitter banks (one for each wavelength), and a two-stage optical switch (OSW). Note that the design of the splitter banks along with the second stage optical switch (OSW-2) ensures that the MC-OSW is strictly non-blocking.

The information at each incoming link is first demultiplexed into w separate wavelengths, each carrying a different signal channel. The separate signals are switched by a first stage optical switch (OSW-1), where the unicast signals are switched directly to the output ports corresponding to their output links. Multicast signals are switched to output ports that are connected to splitter banks (corresponding to the signal wavelength) to be split and then switched/routed by a second stage optical switch (OSW-2) to their respective outputs links. Figure 5.1 shows λ_1 (dashed wavelength) as a unicast signal, and λ_2 (dotted wavelength) as a multicast signal that is switched to the splitter, split and switched back (through OSW-2) to the output links.

To support grooming of multicast traffic, the node architecture shown in Figure 5.1 comprises a grooming fabric (GF). In this architecture, OSW-1 is connected to the GF through a set of transponders. An optical switch with both multicast and grooming capabilities is referred to as, Multicast Capable Optical-Grooming Switch (MC-OGSW). The provisioning of a lightpath/light-tree connection is enabled by the MC-OGSW, where the OSW-1 provides all-optical bypass for a lightpath/light-tree passing through the node without any electronic processing. Alternatively, a lightpath/light-tree can be dropped if the node is the final destination of all the traffic carried by the lightpath/light-tree. Otherwise, the lightpath/light-tree is dropped to the GF where other traffic can be multiplexed (groomed) onto this lightpath/light-tree (i.e., multi-hop grooming) to increase the bandwidth efficiency of wavelength channels. Upon grooming, the traffic is switched either to an output link if this is unicast traffic, or to a corresponding splitter to split the optical signal and forward it to OSW-2, which in turn routes the signals to their different output links. Note that, this will allow traffic to be forwarded from one lightpath/light-tree to another lightpath/light-tree to reach its ultimate destination(s). This is referred to as, multicast multi-hop grooming.

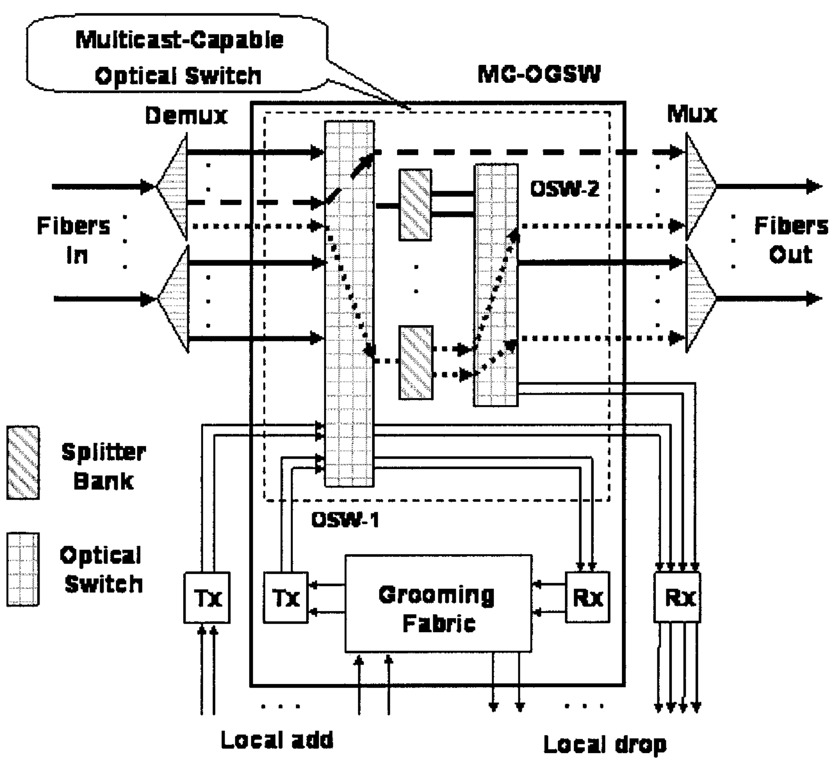

Figure 5.1: Multicast-capable optical-grooming switch architecture

The traffic is assumed to be a combination of unicast and multicast connections according to a given ratio, and each multicast session has only one single source, but a node can be a source of multiple sessions. For each multicast session with source s, G_p represents the maximum percentage of the network nodes that could be destinations, and the number of destinations is uniformly distributed in the interval [2, d], where: $d = \left\lfloor \frac{G_p \times (n-1)}{100} \right\rfloor$, and n is the network size.

5.4 Multicast Routing and Wavelength Assignment

In wavelength-routed networks and without the presence of wavelength converters, a multicast tree requires a dedicated wavelength for each of its branches (links). This problem is referred in the literature as the multicast routing and wavelength assignment (MC-RWA) [12][15][19]. As in the case of routing and wavelength assignment (RWA) for unicast connections, this problem is partitioned into two independent sub-problems, namely multicast routing sub-problem and wavelength assignment sub-problem.

The multicast routing sub-problem (multicast tree problem) is often modeled as the Steiner Minimum Tree problem (SMT), a NP-complete problem [22]. Many heuristics were proposed to find an approximate (sub-optimal) solution to this problem [23][24]. Once the multicast routing sub-problem is solved and the multicast tree is found, the wavelength assignment sub-problem will therefore be the problem of assigning a wavelength along all the links of the corresponding multicast tree [18][25].

Let $G=(V, E, c)$ denotes an undirected graph where V is the set of n vertices in the network, E is the set of m edges (links) in the network, and c is a positive cost function on E.

The SMT problem is defined as the problem to find a connected sub-graph T of G that includes a subset of the vertices $M \subseteq G$ that minimizes $z = \sum_{e \in T} c(e)$ where $c(e)$ is the cost of the edge e. In other words, we need to find T, such that there is a path between a pair of T-vertices, and the total cost of T (i.e., the sum of all its edge costs) is minimized.

In this work, the shortest path tree heuristic (SPT) is used for multicast routing [15]. In SPT, all shortest paths from the source of a multicast session to all its destinations are calculated (using Dijkstra algorithm), and then the paths are combined to form the multicast tree. Since the time needed to calculate all the shortest paths is $O(n^2)$, the time complexity of the SPT algorithm is $O(dn^2)$. However, if we calculate all the shortest paths (from any source to any destination) a priori, the time complexity to calculate a multicast tree using the SPT algorithm reduces to $O(dn)$. Once the multicast tree is found, and assuming there are no wavelength converters, the wavelength assignment sub-problem becomes finding a single available wavelength on all the multicast tree branches. In this work, we use the first-fit scheme for the wavelength assignment sub-problem.

5.5 Design of Hypergraph Logical Topology

Unlike traditional mesh-based WDM networks where only unicast (point-point) traffic is considered, the logical topology of WDM networks with multicast capability must support point-to-multipoint traffic. While the point-to-point based logical topologies are usually modeled by directed graphs whose edges represent the lightpaths, multicast capable networks are best modeled by directed hypergraphs [17][21], in which every two vertices are connected by a hyperarc that represents a light-tree.

5.5.1 Hypergraph

Given a set $S = \{s_1, \ldots, s_n\}$ and family $\varepsilon = \{E_1, \ldots, E_m\}$ of subsets of *S*. we say that ϵ forms a *hypergraph* on *S* if

$$E_j \neq \phi \qquad j = 1, \ldots, m$$
$$\bigcup_j E_j = S$$

The pair *H=(S, ϵ)* is then called a *hypergraph* [26].

The elements $s_1, \ldots, s_n$ of *S* are vertices, and the elements $E_1, \ldots, E_m$ of ϵ are the edges of the hypergraph (called *hyperedges*).

In a hypergraph, we represent E_j by a line enclosing its elements, where vertices *s* and *t* are called *adjacent* if there is a E_j containing both of them; equally, two edges are called adjacent if their intersection is not empty.

A directed hypergraph *H=(S, U)* is defined by a set *S* whose elements are called vertices, and a set *U* whose elements $U_j \in U$ are pairs of subsets of vertices called hyperarcs such as: $U_j = (U_j^-, U_j^+)$ with:

$U_j^- \subset S, U_j^- \neq \phi, U_j^+ \subset S, U_j^+ \neq \phi, U_j^+ \cap U_j^- \neq \phi$. Moreover, we must have:

$$\bigcup_j (U_j^- \cup U_j^+) = S$$

If $U_j = (U_j^-, U_j^+)$ is a hyperarc of *H*, then U_j^- are the initial endpoints of U_j and U_j^+ are the terminal endpoints of U_j. If $|U_j^-| = 1, \forall j$, then the hyperarcs become rooted-trees.

Note that when: $|U_j^-| = |U_j^+| = 1, \forall j$, then the hyperarcs become directed edges and the directed hypergraph is a directed graph. Therefore, a directed hypergraph logical topology (HGLT) is defined as the set of all established lightpaths and light-trees where each of its logical edges is a hyperarc representing an optical lightpath or light-tree.

5.5.2 Illustrative Hypergraph Example

Figure 5.2 shows a hypergraph with four established calls, where there are two wavelength channels available on every link (solid and dotted), and every call is a sub-lambda request of 25% of the channel capacity. In this example, Call#1 is from source *A* to destinations {*C, D*}, Call#2 is from source *H* to destination {*A*}, and Call#3 is from source *D* to destination {*G*}, and are all served on the solid wavelength. Call#4, from source *E* to destinations {*F, G*} is served on the dotted wavelength. Note that electronic processing and multiplexing of traffic is performed only at the end-nodes of the HGLT edges (i.e., at source and destinations of the light-trees), and the traffic is switched/split optically at intermediate nodes of the underlying physical network.

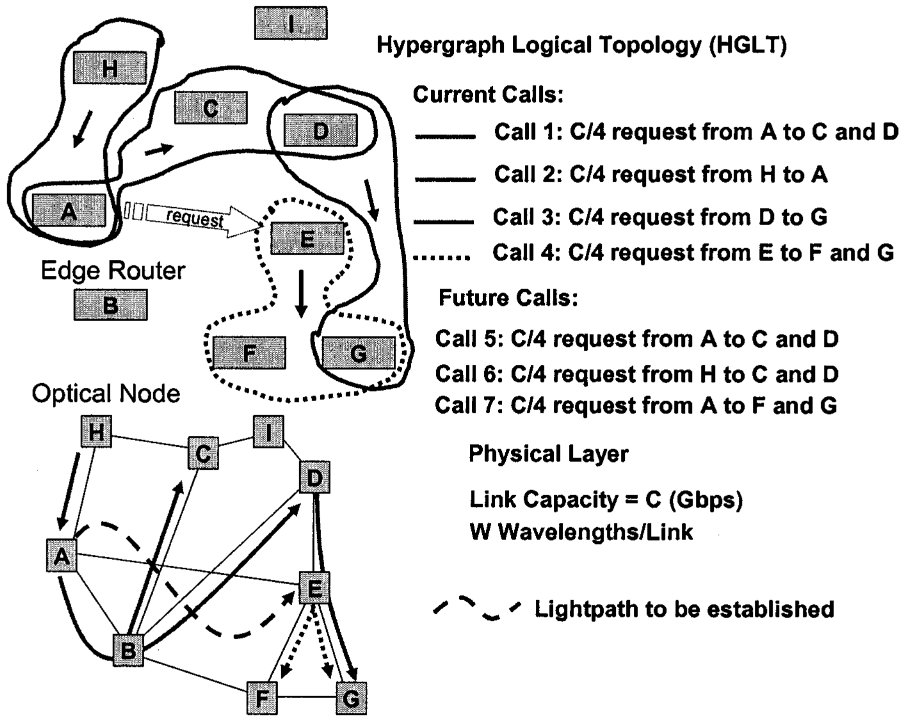

Figure 5.2: Hypergraph logical topology design

5.6 Multicast Grooming Methodologies, Algorithms and Heuristics

The multicast grooming strategy adopted in this work has two main objectives: 1) To utilize the overall network resources as efficiently as possible; 2) To devise grooming algorithms that favors provisioning of multicast traffic demands versus that of unicast (more suitable for serving multicast connection requests). To achieve our objectives, we divide the overall network topology and resources into three different sets: 1) physical topology and its associated available resources 2) logical topology and its associated available resources 3) combined physical and logical topologies (hybrid topology) and its associated available resources. Having identified the various available network topologies and resources, we first devise three different sets of routing and provisioning algorithms, one for each of the three different topologies defined above. Routing/provisioning algorithms developed for each set have only limited access to its own topology and resources. We define the process of selecting the most appropriate blend from amongst these multiple available routing/provisioning schemes to efficiently serve a given unicast/multicast connection request, as our grooming policy. Based on this definition, we then devise a constraint-based grooming strategy that enable us to select the most appropriate blend of these multiple routing/provisioning schemes. We impose the following two constraints on the proposed grooming strategy:

1) The number of logical hops (lightpaths/light-trees) a call can be routed over is limited to a maximum of two hops.

2) Since in multi-hop grooming a node may groom unicast and multicast traffic demands on the same output channel (i.e., same lightpath/light-tree), some destinations on the multicast tree may end-up receiving unintended unicast data leading to a waste of network resources. To alleviate this problem, multi-hop grooming is constrained such that unicast traffic may not be groomed onto multicast traffic, however, multicast traffic can always be groomed onto unicast traffic.

A connection request can be served using the physical layer resources (MC-RWA), the logical layer resources (logical routing/provisioning), or a combination of both (hybrid routing/provisioning).

5.6.1 The Routing/Provisioning Problem

5.6.1.1 Physical Routing/Provisioning:

This work assumes a static multicast routing and dynamic wavelength assignment algorithm that attempts to solve the routing problem and the wavelength assignment problem independently by dividing the problem into two sub-problems: the multicast routing problem and the wavelength assignment problem. This is the MC-RWA problem that was described earlier in Section 5.4, where the cost of a physical link *(i, j)* is defined as follow:

$$P_{ij} = \begin{cases} 1 & link\ (i, j)\ exist \\ \infty & link\ (i, j)\ doesn't\ exist \end{cases} \tag{5.1}$$

As explained previously, the SPT multicast routing algorithm and the first-fit wavelength assignment scheme are used to solve the MC-RWA problem.

5.6.1.2 Logical Routing/Provisioning:

The logical routing/provisioning of a unicast/multicast request is achieved by considering established lightpaths and light-trees as directional logical links that comprise the hypergraph logical topology. The HGLT construction is performed whenever a call is attempted to be served logically, therefore, the HGLT is dynamically changing every time a lightpath/light-tree is set-up or torn-down in response to the dynamic unicast/multicast traffic demands. Typically a multicast request may either be routed over a single light-tree (i.e., single hyperarc or single-hop) or it may span multiple light-trees (i.e., multi-hyperarcs, or multi-hops).

In single-hop case, a connection is allowed to traverse a single lightpath/light-tree (same wavelength is used throughout the entire route from source-to-destination(s)), which means that only end-to-end traffic grooming (multiplexing) is allowed. In multi-hop case, a connection is allowed to traverse multiple lightpaths/light-trees, i.e., a connection can be dropped/terminated at an intermediate node and multiplexed with other low-speed unicast/multicast connections on different lightpaths/light-trees (wavelengths) before it reaches its destination(s). In the case of a single-hop route, only calls with the same source-destination(s) can be multiplexed onto one lightpath/light-tree. On the other hand, in the case of a multi-hop route, calls with different source-destination(s) can be multiplexed into the same lightpath/light-tree.

The cost function used for routing calls over the HGLT (logical routing) between a node i and its destination group d_i is defined as the following:

$$L_{i,d_i} = \begin{cases} 1 & R_{BW} >= RQ_{BW} \\ \infty & R_{BW} < RQ_{BW} \ or \ R_{BW} = C \end{cases} \tag{5.2}$$

Where, R_{BW} is the residual bandwidth of the light-tree connecting the source i and its destination group d_i, R_{QBW} is the required bandwidth of a multicast connection request, and C is the channel capacity.

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5.6.1.3 Hybrid Routing/Provisioning:

A unicast/multicast request can be routed/provisioned over a combination of existing lightpaths/light-trees (logical routing) and a newly created lightpath/light-tree (physical routing, e.g., RWA/MC-RWA). In this approach, the optical layer must keep updated databases about both the logical and physical topologies connectivity along with resource utilization across both layers [27][28]. In this work, the idea of a hybrid provisioning approach is defined to find a combined route of an existing logical segment (light-tree) and an un-provisioned physical segment (lightpath) that needs to be set up.

To illustrate the concept of hybrid provisioning, assume the case depicted in Figure 5.2. Let Call#1 to Call#6 arrive at the network and being served as shown in the figure. Suppose now that Call#7 arrives at the network requesting service from A to $\{F, G\}$. Since the link between E and $\{G\}$ is completely utilized at the wavelength level (both wavelengths are used), and no logical connectivity exists from A to $\{F, G\}$, traditionally this call would have been blocked. Under the hybrid approach however, node A knows that there exists a TDLT to $\{F, G\}$ that has originated at E. Therefore A requests from the physical topology a FSLP to $\{E\}$ and if enough resources are found and a successful connection is established, call#7 is served by utilizing the new established FSLP from A to $\{E\}$ and the already established TDLT from E to $\{F, G\}$.

5.6.2 Multicast Traffic Grooming Strategy and Heuristics

The critical remaining question that needs to be addressed in this section is how to combine the above developed multiple routing/provisioning approaches to serve unicast/multicast traffic demands as efficiently as possible using the overall global network resources. In other words, how these global network resources should be allocated to a given request if multiple routing/provisioning schemes are available. Should a new request be accommodated using one or more existing lightpaths/light-trees first? Is it more appropriate to set up a new lightpath/light-tree first? Or should it be accommodated using a combination of both in a sequential order similar to conventional sequential routing/provisioning approaches used for unicast traffic grooming [7][11][29]? It is important to emphasize that existing sequential unicast grooming strategies and algorithms along with associated simulation results [7][11][29] can't be taken as guidelines when considering multicast traffic. Thus, conventional sequential routing/provisioning approaches used for unicast traffic grooming should be revisited (after being modified to tailor provisioning of multicast traffic) and thoroughly examined, to test its effectiveness for grooming multicast traffic as well.

To answer these questions, we first develop several different sequential multicast/unicast grooming heuristics by means of interchanging the search space between the physical and logical layers. Second, guided by the simulation results of the proposed sequential multicast grooming heuristics, we augment the sequential grooming heuristics (the one that gives best performance results) by a hybrid approach to implement a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches.

5.6.2.1 Logical-First Sequential Routing:

With this algorithm, the network first tries to accommodate the call on the logical topology making use of the already existing connections. Depending on the grooming approach to be used (i.e., Single-Hop or Multi-Hop), if no available single/multi-hop route were found on the logical topology, the source node sends a request to the ingress

OXC to set-up a light-tree on the physical topology to all the multicast destinations. Then, the ingress OXC invokes its multicast routing and wavelength assignment (MC-RWA) algorithm to set-up a new light-tree to the destinations. If the MC-RWA is unsuccessful, the call is blocked. Depending on the number of logical hops, this algorithm can further be classified into the following two schemes:

a) Logical-First Sequential routing with Single-Hop grooming (LFSEQSH): With this scheme, the network first tries to service the call using a single-hop logical hyperarc only (i.e., single light-tree). If the search is successful, the call is serviced. Otherwise (i.e., if the search fails), the ingress OXC invokes its MC-RWA algorithm to set-up a light-tree on the physical topology to all the multicast destinations. If the MC-RWA is unsuccessful, the call is blocked.

b) Logical-First Sequential routing with Multi-Hop grooming (LFSEQMH): This algorithm is similar to the "*LFSEQSH*", however, the search on the logical topology is allowed to include two logical hops instead of a single-hop. Therefore, multi-hop grooming is performed in a sequential way by attempting the logical layer first. Note that throughout the remaining part of this chapter, "multi-hop" means only two hops. The algorithm is summarized below in Table 5.1.

5.6.2.2 Physical-First Sequential Routing:

With this approach, the network attempts to accommodate a call on the physical layer first. If the new light-tree is established successfully, a new logical/virtual hyperarc (light-tree) is created in the logical layer. If the physical routing fails, then routing on logical topology is attempted. Similar to the logical-first approach, depending on the number of logical hops, this algorithm can also be classified into the following two schemes:

a) Physical-First Sequential routing with Single-Hop grooming (PFSEQSH): This scheme is similar to the *LFSEQSH*; however, the search is now attempted on the physical layer first. Therefore, single-hop grooming is performed in a sequential way by attempting the physical layer first.

b) Physical-First Sequential routing with Multi-Hop grooming (PFSEQMH): This scheme is similar to the *LFSEQMH*; however, the search is now attempted on the physical layer first. Therefore, multi-hop grooming is performed in a sequential way by attempting the physical layer first.

5.6.2.3 Combined Sequential and Hybrid Routing

In this scheme, we combine the hybrid provisioning approach with sequential provisioning approaches to achieve a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches. Specifically, we combine the hybrid approach with that of *LFSEQMH* sequential approach and denote the resultant grooming scheme as Logical-First Hybrid Routing (*LFHYB*). The reason for choosing the *LFSEQMH* algorithm is that, as will be shown below, this scheme gives the best performance results from amongst all the sequential schemes described above.

The steps for implementing this scheme are exactly the same as *LFSEQMH* except that upon the failure of Step 4 in Table 5.1 {no existing lightpath (FSLP) that directly connects the source of the requested multicast session and the source of a TDLT found on the logical topology}, rather than going back to Step 3; the algorithm first tries to set up a new lightpath (by invoking RWA on the physical topology) between the source of the requested multicast session and the source of the TDLT. If the RWA succeeds, the combination of the newly provisioned lightpath and the existent TDLT will be used to serve the new multicast request. If it fails, then the algorithm goes back to Step 3 in Table 5.1. Note that more than one TDLT can be found, however we only consider the "first-available". The algorithm is summarized below in Table 5.2.

Table 5.1: LFSEQMH Algorithm

<u>Step 1:</u> For each multicast connection request, check whether a logical single light-tree with available bandwidth and with the same source and destinations as those of the multicast connection request exists. If yes, go to **Step 5**, else go to **continue**.
<u>Step 2:</u> Search logical topology for an existing single light-tree with available bandwidth whose destinations are the same destinations as the multicast connection request (i.e., **TDLT**). If yes, go to **Step 4**, else go to **continue**.
<u>Step 3:</u> Invoke physical provisioning (i.e., **MC-RWA**), if a multicast tree was found and a wavelength was available, go to **Step 5**, else **stop** and block the connection request.
<u>Step 4:</u> Identify the source of **TDLT** and search the logical topology for a lightpath (i.e., **FSLP**) between the original source of the request and the source of TDLT. If yes, go to **continue,** else go back to **Step 3**
<u>Step 5:</u> Serve the request by reserving the bandwidth along the corresponding lightpath and/or light-tree and update the logical topology; the connection request is satisfied.

Table 5.2: LFHYB Algorithm

Step 1: For each multicast connection request, check whether a logical single light-tree with available bandwidth and with the same source and destinations as those of the multicast connection request exists. If yes, go to **Step 6**, else go to **continue**.
Step 2: Search logical topology for an existing single light-tree with available bandwidth whose destinations are the same destinations as the multicast connection request (i.e., **TDLT**). If yes, go to **Step 4**, else go to **continue**.
Step 3: Invoke physical provisioning (**MC-RWA**), if a multicast tree was found and a wavelength was available, go to **Step 6**, else **stop** and block the connection request.
Step 4: Identify the source of **TDLT** and search the logical topology for an existing lightpath (i.e., **FSLP**) between the original source of the request and the source of **TDLT**. If yes, go to **Step 6,** else **continue.**
Step 5: Invoke physical provisioning (**MC-RWA**), between the original source of the request and the source of **TDLT**, if succeeded**, continue;** else go back to **Step 3.**
Step 6: Serve the request by reserving the bandwidth along the related lightpath and/or light-tree and update the logical topology, thus the connection request is satisfied.

5.7 Performance Evaluation

The performances of the proposed grooming algorithms are evaluated through the simulation of several network topologies that demonstrated similar conclusions. We present results here for the 14 nodes, 21 links NSF network. Unless otherwise specified, the following assumptions and parameters are used throughout the simulation:

- Each node in the network is an MGC-OSW with full splitting and full grooming capability, but with no wavelength conversion capability.
- Each adjacent node pair is interconnected by one (bi-directional) fiber and each fiber carries 64 wavelengths.
- Multicast traffic is assumed to constitute half of the total traffic and the other half is unicast traffic.
- Signal power loss due to light splitting is neglected because optical amplifiers are used.
- A dynamic traffic model is used. Call requests arrive at each node according to a Poisson process and an arrival session is equally likely to be destined to any node(s) in the network. For both unicast and multicast sessions, the low-speed connection requests are 25% of the wavelength capacity
- For each multicast session, the destination group size G_p is equal to 30%, where G_p is the maximum percentage of the network nodes that could be destinations.

The simulation results of the proposed grooming algorithms is compared with those of two baseline conventional multicast schemes: In the first one, a multicast connection request is served as multiple independent unicast connections (UC). In the second scheme, each multicast request is served on separate light-tree (MC-RWA) without taking into account the grooming capability of the optical node.

Figure 5.3 shows the blocking probability (BP) of the proposed sequential grooming schemes. As can be seen from the figure, the performance of the *"LFSEQMH"* scheme outperforms all other schemes. Note also that the performance of both logical-first schemes (*LFSEQMH* and *LFSEQSH*) outperform those of physical-first schemes (*PFSEQMH* and *PFSEQSH*). This is in sharp contrast to the sequential unicast grooming algorithms where it has been shown that the performance of the physical-first scheme is the one that outperforms all other sequential unicast schemes [7][11][29].

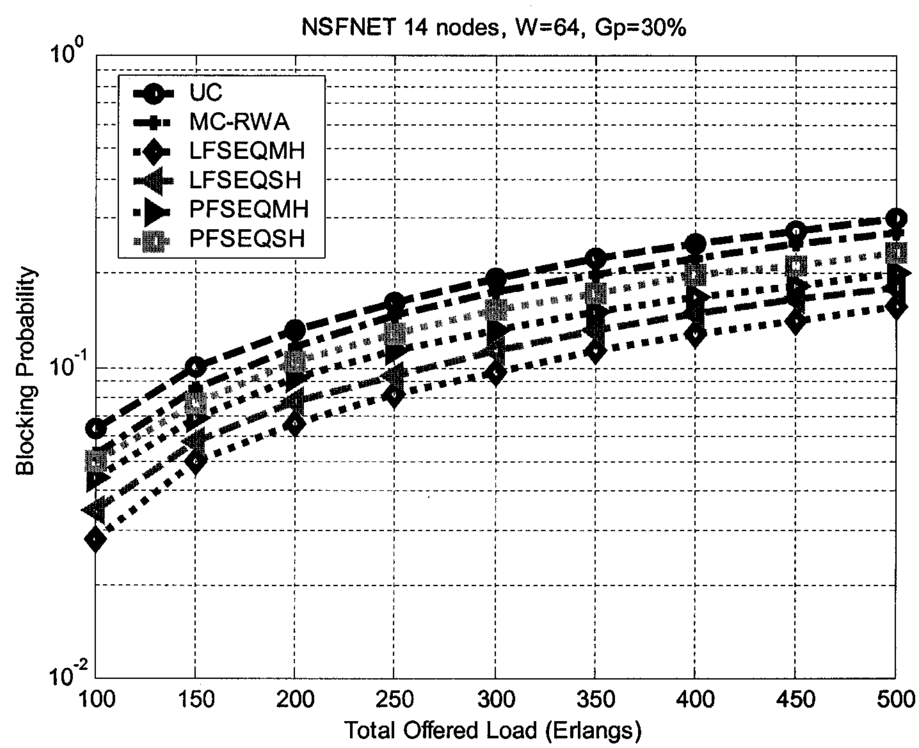

Figure 5.3: Blocking probability of proposed sequential approaches and conventional approaches

We define the grooming gain as the percentage in network performance gain (in terms of blocking probability) achieved when a grooming scheme is used versus a non-grooming scheme. For instance, if *"LFSEQMH"* is used as a grooming algorithm, and *"MC-RWA"* is used as a conventional non-grooming algorithm, then, the grooming gain of *"LFSEQMH"* is defined as follows:

$$G_{LFSEQMH} = \frac{BP_{MC-RWA} - BP_{LFSEQMH}}{BP_{MC-RWA}} \times 100 \tag{5.3}$$

Using a grooming scheme such as *"LFSEQMH"* results in at least 40% in network performance gain (grooming gain) when compared to a non-grooming scheme such as "MC-RWA" (see Figure 5.4). Note that the grooming gain is almost independent of the total network offered load since the gain is relative to "MC-RWA", and as the load increases, both schemes will have higher blocking probability.

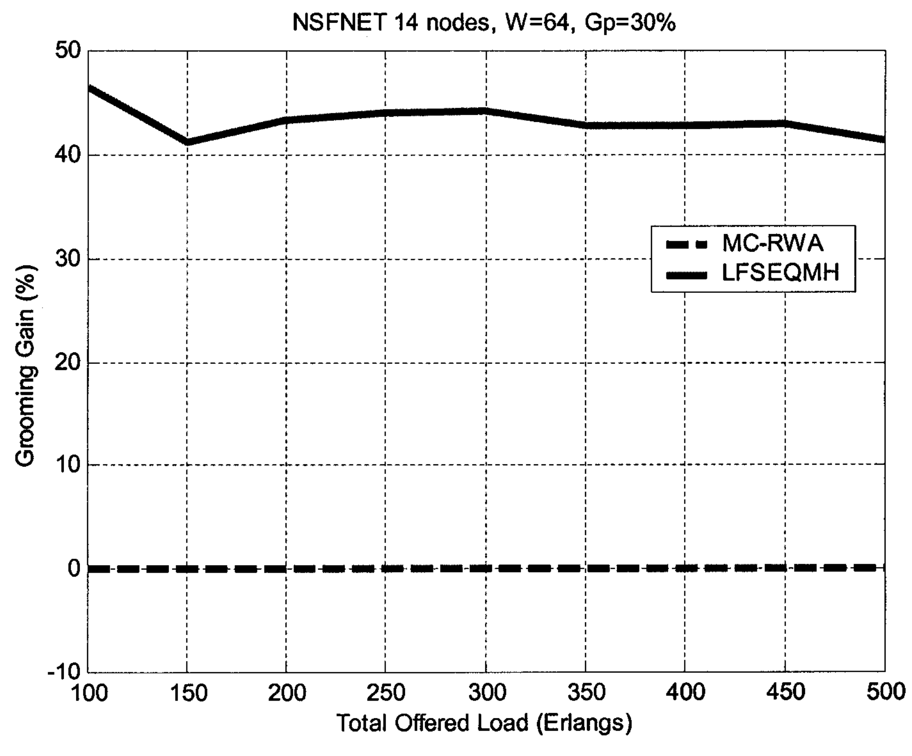

Figure 5.4: Grooming Gain vs. Network Load

Figure 5.5 shows the grooming gain versus the multicast group size (G_p). As can be seen from Figure 5.5; the grooming gain decreases with the increase of multicast group size. This is because as the number of multicast destinations increases, the probability of finding a single-hop light-tree or a combination of single-hop lightpath and a single-hop light-tree with the same exact multicast destinations decreases. Hence, as expected, the grooming gain will decrease.

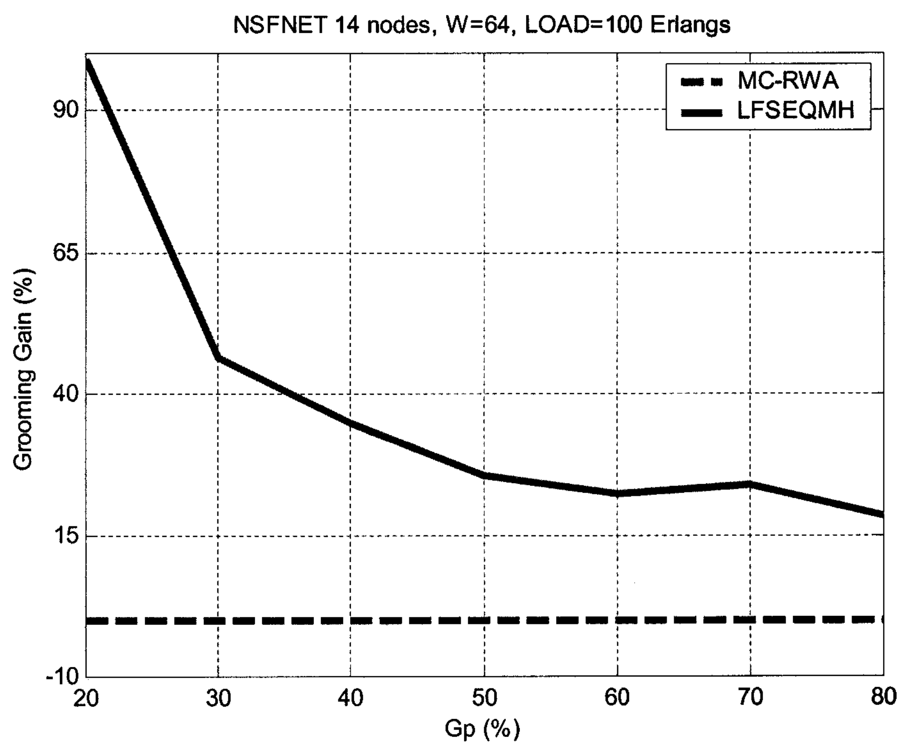

Figure 5.5: Grooming Gain vs. Multicast Group Size

Figure 5.6 shows the percentage of multicast traffic served on the logical layer (both single-hop and multi-hop) as well as on the physical layer when *"LFSEQMH"* is used. As can be seen from the figure, the total number of groomed multicast sessions that are served on the HGLT (logical layer) is between 30% and 50% of the total multicast connections requests. Note that the number of single-hop multicast sessions being served on the HGLT is higher than those of the multi-hop. Note also that the percentage of single-hop multicast sessions increases with the offered load while the percentage of the multi-hop multicast sessions does not change much. This is due to the fact that as the offered load increases, more multicast requests will arrive, which leads to a highly connected HGLT. Hence it is more probable to find existing light-trees for grooming single-hop sessions, leading to the observed increase of multicast sessions that are groomed with single-hop routes.

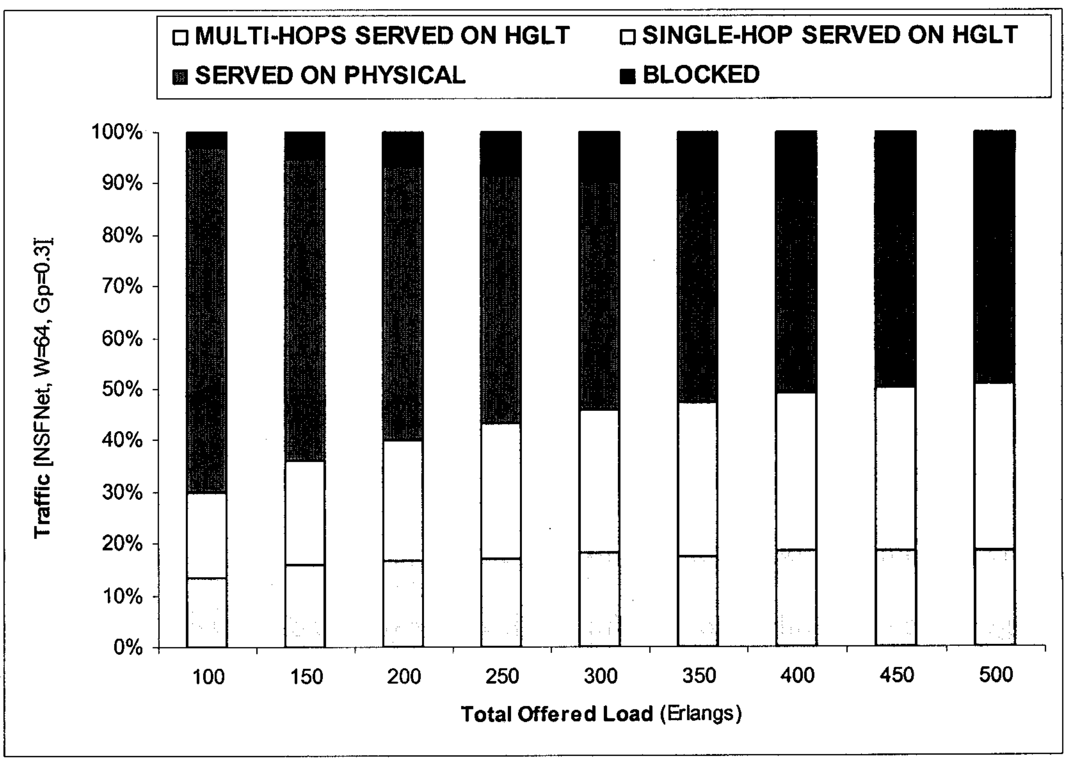

Figure 5.6: Percentage of Single-Hop and Multi-Hop groomed sessions for "LFSEQMH"

To assess the performance of a multi-hop grooming scheme versus that of a single-hop, we define the multi-hop gain (*MHG*) to be the percentage in performance gain (in terms of blocking probability) achieved when using a multi-hop routing approach over a single-hop approach. Thus, MHG is defined as follows:

$$MHG = \frac{BP_{SH} - BP_{MH}}{BP_{SH}} \times 100 \tag{5.4}$$

Using (5.4), we calculate the multi-hop gain of *LFSEQMH* with respect to *LFSEQSH.* Figure 5.7 shows the multi-hop gain versus the percentage of multicast traffic demands. As it can be seen from Figure 5.7, with 20% multicast traffic, there is no significant advantage as most of the traffic is unicast.

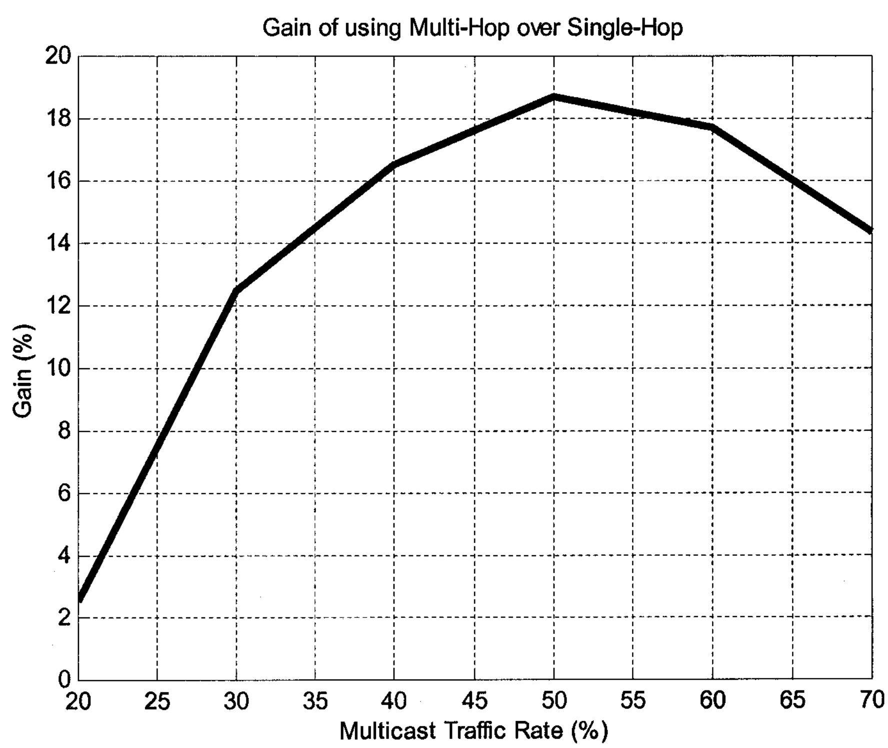

Figure 5.7: Multi-Hop Gain (Load = 100 Erlangs; Gp=30%)

However, when the percentage of multicast traffic increases, the probability of finding a combination of existing lightpath/light-tree for multi-hop routing increases, resulting in a corresponding increase of the multi-hop gain, but up to a certain limit (percentage of multicast sessions are 50% or less). As the percentage of multicast sessions exceeds 50%, the gain decreases again. This is because, with more multicast traffic, the probability of finding a single connection (single-hop lightpath) between the source of the multicast session and an intermediate source (the source of a TDLT) will decrease (less unicast traffic).

We now examine the impact of combining both the hybrid and sequential approaches (*LFHYB*) on the grooming capability of multicast sessions and compare its performance with that of the sequential approach (*LFSEQMH*). Figure 5.8 shows the percentage of additional multicast sessions that are groomed on the logical topology when the hybrid approach (*LFHYB*) is used with respect to those that would have been groomed if the sequential logical first approach (*LFSEQMH*) is used. As expected, the percentage of multicast sessions that are served using the hybrid scheme (*LFHYB*) is always greater than that of the sequential scheme (*LFSEQMH*). For instance, at low loads (100 Erlangs), the figure shows that the hybrid approach is able to groom almost 85% more multicast sessions than the logical sequential approach. This is very critical because blocking a unicast session is usually less expensive than blocking a multicast session. Hence, by allowing more multicast sessions to be served, we are improving the network performance. Note, however, as the load increases, the additional percentage of groomed multicast sessions decreases (down to almost 30%). This is because the hybrid approach uses both logical and physical resources to groom these additional multicast sessions. At high loads, physical resources are almost depleted and, therefore, the hybrid approach performance approaches that of the logical sequential approach (high loads means high logical connectivity and less available physical resources which are required for hybrid provisioning).

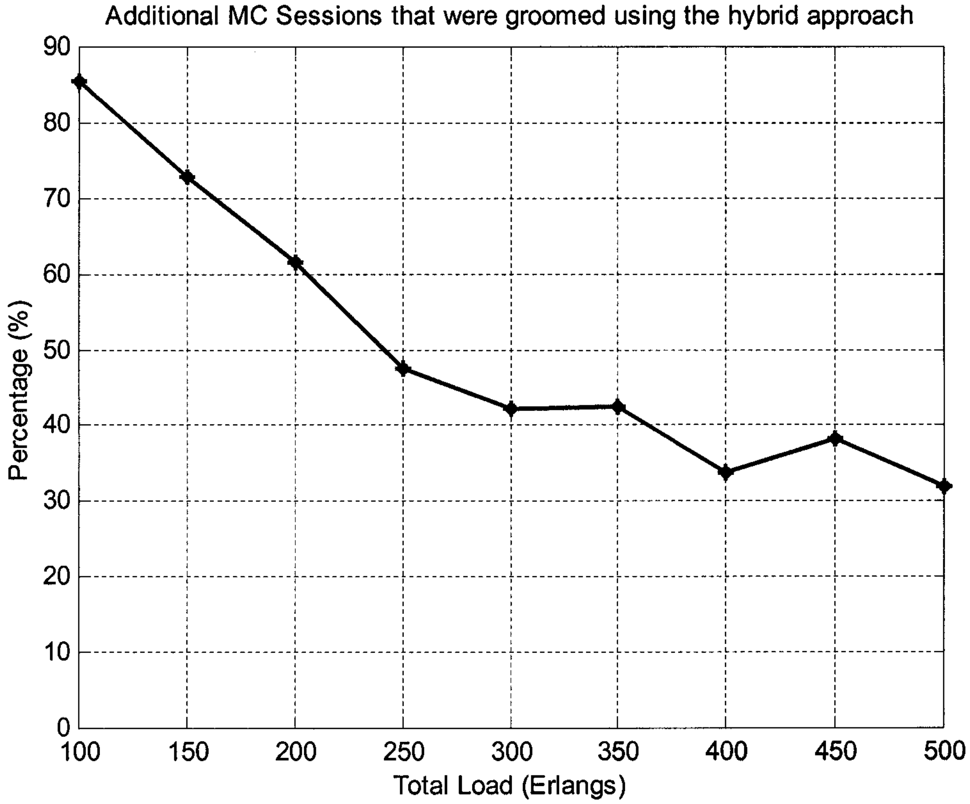

Figure 5.8: Additional groomed multicast sessions when "LFHYB" is used instead of "LFSEQMH"

Figure 5.9 compares the percentage of the total traffic (both unicast and multicast) that is groomed on the logical topology only, for both *LFHYB* and *LFSEQMH* schemes. The results shown in Figure 5.9 further confirm the results of Figure 5.8. With more calls served purely logically, the hybrid approach minimizes the total cost of the network by maximizing the utilization of the existent logical resources.

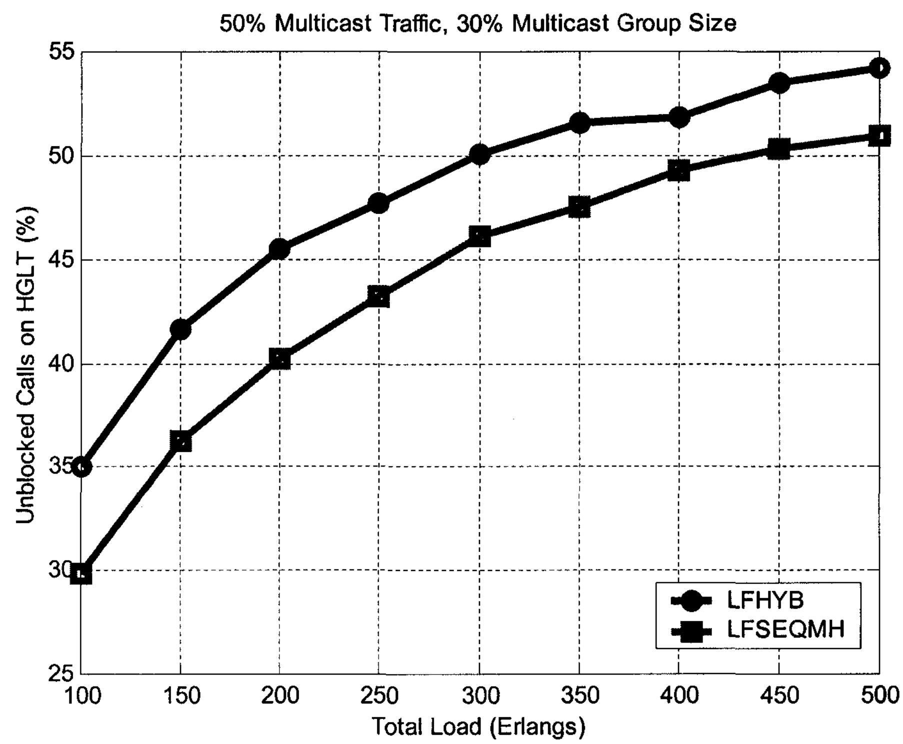

Figure 5.9: Percentage of calls that are purely served on HGLT

Finally, we assess the performance of the above multi-hop grooming approaches when the second constraint imposed on our grooming strategy (unicast traffic may not be groomed onto multicast traffic) is relaxed. When the second constraint is relaxed, we redefine the original restricted *"LFSEQMH"* scheme as a Non-Restricted Logical-First Sequential Routing (*NRLFSEQMH*) scheme. Figure 5.10 compares the performance of the restricted *"LFSEQMH"* scheme with that of the *"NRLFSEQMH"* scheme. As can be seen from the figure, at low loads, the performance of the *"NRLFSEQMH"* scheme outperforms that of the original *"LFSEQMH"* scheme. This is because at low loads more resources are still available and the impact of wasting bandwidth (some destinations on the multicast tree end-up receiving unintended unicast data) is negligible.

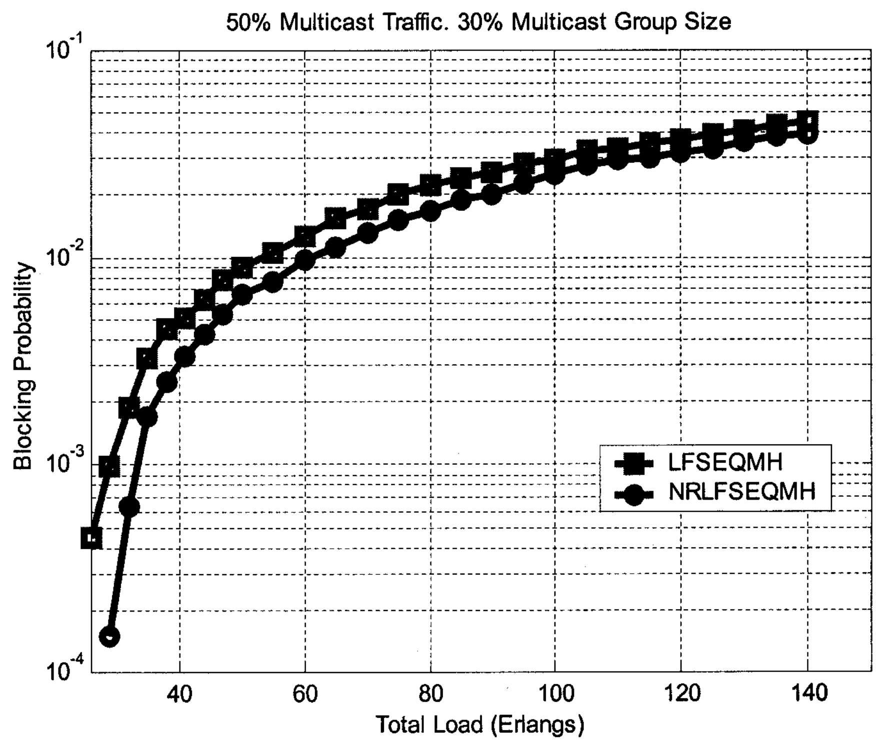

Figure 5.10: Performance of Non-Restricted Approach at Low Loads

However, at higher loads, as shown in Figure 5.11 , the performance of the original restricted grooming algorithm *"LFSEQMH"* outperforms that of the *"NRLFSEQMH"* scheme. This is because at higher loads, available resources are now scarce and the impact of wasting bandwidth has deleterious effect (increases blocking probability) on the overall network performance.

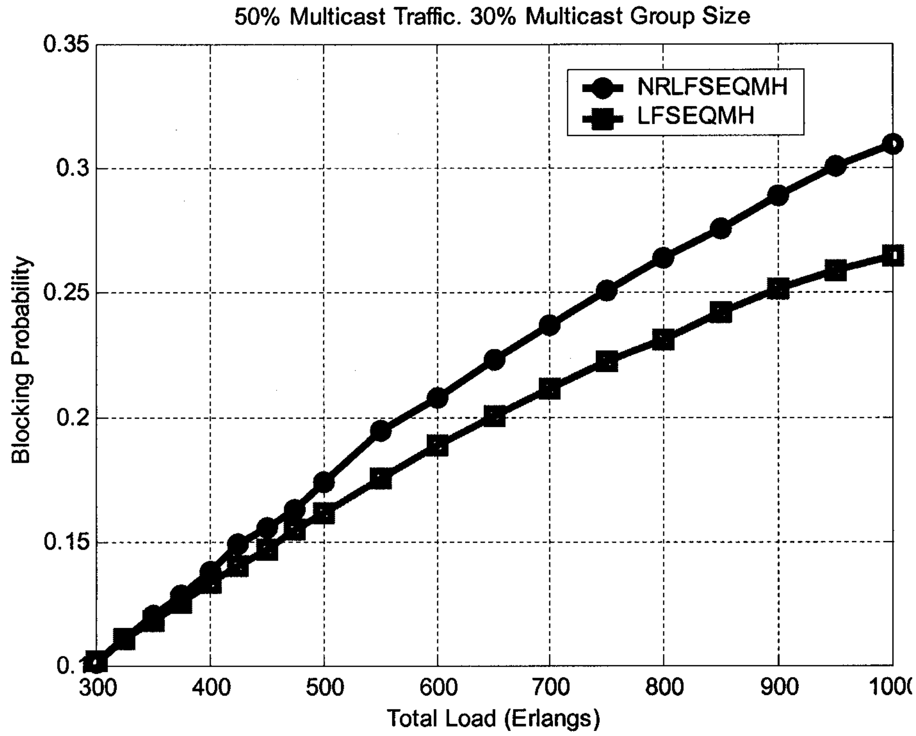

Figure 5.11: Performance of Non-Restricted Approach at High Loads

5.8 Conclusions

This chapter has addressed the problem of dynamically provisioning both low-speed unicast and multicast connection requests in mesh-based WDM optical networks. Several routing/provisioning schemes to dynamically provision multicast connection requests have been presented. We have devised a constraint-based grooming strategy to utilize the overall network resources as efficiently as possible. Based on this strategy, several different sequential multicast grooming heuristics have been developed. Guided by the simulation results of the sequential multicast grooming heuristics, we have augmented the sequential grooming heuristics by a hybrid approach to implement a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches.

Numerical results have indicated that the proposed grooming approaches use the network resources more efficiently compared to the non-grooming and unicast approaches. The results have also shown that the percentage of multicast sessions that are served on the logical topology using the hybrid scheme is always greater than that of the sequential approaches. This is very important because blocking a unicast session is usually less expensive than blocking a multicast session. Finally, the hybrid approach increased the percentage of both unicast and multicast calls that were served purely on the logical topology; hence, it minimized the total cost of the network by maximizing the utilization of the existent logical resources.

Chapter 6

6. Dynamic Provisioning of Survivable Unicast and Multicast Traffic in Mesh-Based WDM Networks

6.1 Introduction

In optical networks, it is essential to have backup mechanisms to prevent the loss of information due to fiber cuts or equipment failures, which may occur often enough to cause service disruption. This loss could be crucial in the case of the multicast traffic where a link in a "light-tree" carries traffic to multiple destinations. Various protection schemes are used in today's optical networks and survivable optical networks have been studied extensively in the literature [1][2][3][4]. Many schemes have been proposed to protect optical networks against single link failure, however most of the work considered only unicast traffic [1][2][3][4].

In general, studies on WDM mesh network survivability fall under two categories: pre-designed protection and dynamic restoration [4]. Dynamic restoration implies the discovery of spare capacity dynamically in the network to restore the affected services; that is, the resources used for recovery are not reserved at the time of connection establishment, but are chosen from available resources when the failure occurs. On the other hand, in the pre-planned protection, recovery from network failures is based on pre-planned schemes and it usually relies on resources (fibers, wavelengths, switches, etc.) dedicated to protection purposes. Resources are reserved for recovery from failures at either connection setup or network design time, and kept idle when there is no failure. From this point of view, the use of capacity is not very efficient, but on the other hand, the level and speed of recovery from a failure can be guaranteed.

The problem of protecting purely multicast connections in WDM mesh network has recently started to receive some attention in the literature [5][6][7]. In fact, the future WDM traffic is heterogeneous in nature and only part of the traffic is multicast and the rest is unicast, therefore we should expect the presence of both unicast and multicast traffic in future WDM networks. In this work, we study the problem of dynamic provisioning of survivable heterogeneous unicast and multicast traffic in WDM networks. Specifically, we propose new protection schemes to provision and protect unicast and multicast connection requests against single-link failures in WDM-mesh networks and we compare them with other proposed schemes in the literature. The remainder of the chapter is structured as follows. Section 6.2 outlines the network model and the node architecture. The protection approaches are described in section 6.3. Section 6.4 presents the performance evaluation and the chapter concludes in Section 6.5.

6.2 Network Model and Node Architecture

We consider a WDM network with n optical nodes interconnected by bi-directional fiber links, where each link carries w wavelengths and each node is equipped with a multicast-capable all-optical switch (MC-OSW) with p input ports (fibers) and p output ports. The multicast capability of MC-OSW is supported via optical splitter banks, where a $p \times p$ optical splitter bank splits the input signal into p identical output signals [8]. Note that splitter banks may be enhanced to compensate for the power loss, wavelength conversion, and signal regeneration. A $p \times p$ MC-OSW that supports w wavelengths consists of p ($1 \times w$) demultiplexers, p ($w \times 1$) multiplexers, w splitter banks (one for each wavelength), and a two-stage optical switch (OSW). Note that the design of the splitter banks along with the second stage optical switch (OSW-2) ensures that the MC-OSW is strictly non-blocking.

The information at each incoming link is first demultiplexed into w separate wavelengths, each carrying a different signal channel. The separate signals are switched by a first stage optical switch (OSW-1), where the unicast signals are switched directly to the output ports corresponding to their output links. Multicast signals are switched to output ports that are connected to splitter banks (corresponding to the signal wavelength) to be split and then switched/routed by a second stage optical switch (OSW-2) to their respective outputs links. Figure 6.1 shows λ_1 (dashed wavelength) as a unicast signal, and λ_4 (dotted wavelength) as a multicast signal that is switched to the splitter, split and switched back (through OSW-2) to the output links.

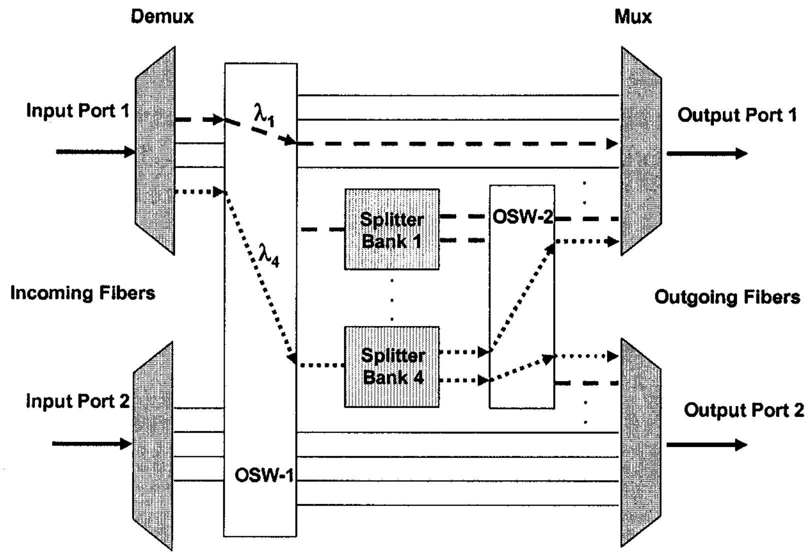

Figure 6.1: A 2x2 MC-OSW that supports 4 wavelengths

The traffic is assumed to be a combination of unicast and multicast connections according to a given ratio, and each multicast session has only one single source, but a node can be a source of multiple sessions. For each multicast session with source "*s*", we define the multicast group size (G_p) to be the maximum percentage of the network nodes that could be destinations. Therefore, for a given multicast session, the number of destinations will uniformly distributed in the interval [*2, d*], where: $d = \left\lfloor \frac{G_p \times (n-1)}{100} \right\rfloor$, and *n* is the network size.

6.3 Protection Approaches

6.4.1 Link-Disjoint Tree Protection

One approach to protect multicast traffic is to calculate primary (working) and link-disjoint backup (protection) multicast trees. Two trees are said to be link-disjoint if they do not share any link along their edges. This will provide 1+1 dedicated protection where the traffic is transmitted simultaneously on both working and protection trees, and in case of failure, the affected multicast destinations are required to reconfigure their switches to switch from working tree to protection tree to receive the backup signal, i.e., *non-signaled* switchover. . The main problems of this approach are the excessive use of network resources; therefore, by trying to serve and protect a multicast session we may block a large number of future connections [5]. In fact, finding link-disjoint trees depends on the heuristics used to find the multicast tree as well as the difficulties, in general, in finding such trees in mesh networks. The less optimum the heuristic, the more difficult is to find link-disjoint primary and backup trees. For example, in Figure 6.2, if the SPT heuristic described in chapter 5 (Table 6.1) is used to calculate the multicast primary and backup trees (Backup tree can be calculated by applying the SPT heuristic on the remaining graph after we remove the links associated with the primary tree) it is impossible to find link-disjoint tree from the source node "s" to the multicast destinations "d_1", "d_2" and "d_3" (Figure 6.2 (a)). However, as it is shown in Figure 6.2 (b), the network has sufficient resources to provision and protect the multicast session using link-disjoint multicast trees. In fact, link-disjoint multicast trees depicted in Figure 6.2 (b) are calculated based on our proposed optimized SPT heuristic (OSPT) that is described in Table 6.2. For example, in Figure 6.2 (b), the minimum-cost path from the source node "s" to the destination "d_1" is calculated (Table 6.2: Step 2). The minimum-cost path is {s, a, d_1}. After that, the cost for all the links involved in the minimum-cost path is set to zero to increase the sharing in the primary tree (Table 6.2: Step 3). Steps 2 and 3 are repeated for "d_2" and the returned minimum-cost path for "d_2" is {s, a, d_2}. With cost of links (s-a), (a-d_1) and (a-d_2) is zero, the minimum-cost path from "s" to the multicast destination "d_3" is now {s, a, d_2, d_3} instead of the shortest path {s, b, d_3}.

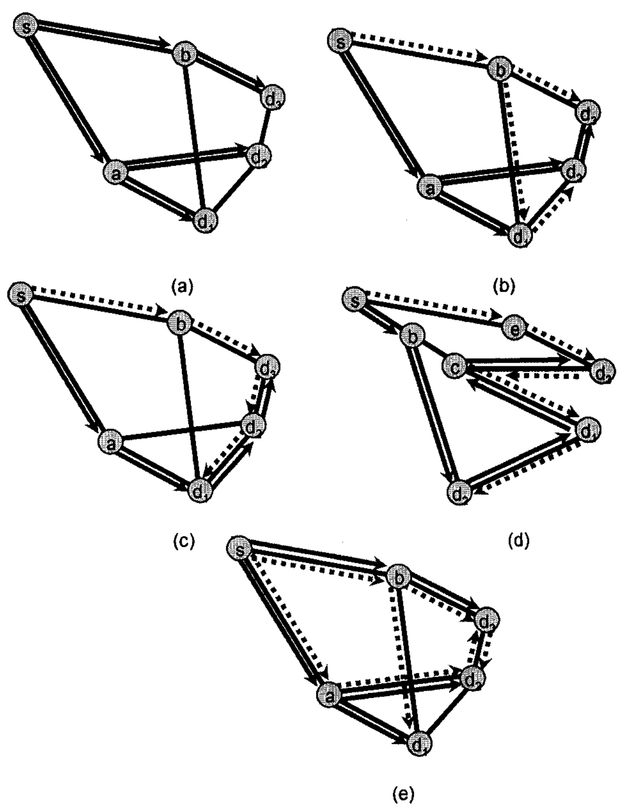

Figure 6.2: Calculating primary (solid) and backup (dotted) trees/routes from source "s" to destinations {d_1, d_2, d_3}.

Table 6.1: SPT Heuristic

Step 1: For a multicast request with *"s"* is the multicast source, find the shortest paths from *"s"* to all the multicast destinations (using Dijkstra algorithm).
Step 2: Merge all the shortest paths together and construct a multicast tree (i.e., SPT)

Table 6.2: OSPT Heuristic

Step 1: For every multicast destination of the multicast session with source *"s"*, repeat steps 2 and 3.
Step 2: Find the minimum-cost path from *"s"* to the multicast destination (using Dijkstra algorithm).
Step 3: Update cost = 0 for all the links included of the already-found path
Step 4: Merge all the minimum-cost paths together and construct a multicast tree (i.e., OSPT)

6.4.2 Arc-Disjoint Path Protection

The notion of "arc-disjointness" or "directed-link disjointness" was introduced in the literature to improve network performance by reducing the usage of the network resources while providing dedicated protection against link failure [4]. Therefore, arc-disjoint paths were defined to be paths that may share a link in the opposite direction. In [6], it was shown how arc-disjoint primary and backup trees can be used to protect a multicast session against any fiber cut through appropriate switch reconfigurations.

The collapsed rings heuristic (CR) proposed in [7] to protect multicast sessions in WDM-mesh networks could be used to calculate arc-disjoint paths to protect the unicast and multicast traffic against any fiber cut that may occur in the network. Using this approach we calculate primary and backup multicast paths starting from the source node and visiting all the multicast destinations according to the Table 6.3.

Table 6.3: Collapsed Rings Heuristic (CR)

Step 1: Given a source "s" and multicast destinations $\{d_1, d_2, \ldots d_n\}$, form a ring set of vertices $\{v_1, v_2, \ldots v_n\}$, where v_1 is the source "s" and $v_2, \ldots v_n$ are the multicast destinations.
Step 2: For primary path, calculate the shortest paths from v_i to v_{i+1} where $1 \le i \le n-1$ and remove all the links along the path. If node v_x is included in the path, then remove the vertex v_x from the ring set.
Step 3: Repeat **Step 2** until all the vertices from the ring set are chosen and the primary path is created.
Step 4: For backup path, find the shortest path from source to the last destination in the backup path and traverse the primary path backwards until the first destination is reached.

For example, as you can see in Figure 6.2 (c), it is clear that if any link fails in the network, and with appropriate switch reconfiguration, the primary (solid) and backup (dotted) paths ensure that the signal delivery is not disrupted from source "s" to the multicast destinations $\{d_1, d_2, d_3\}$. Note that, if any link that carries the traffic in both directions (e.g., (d_1-d_2)) fails, it is clear that all multicast destinations can receive the bit streams through either primary path (i.e., d_1) or the backup path (i.e., d_2 and d_3). However, the CR heuristic is not optimum, and it might lead to blocking sessions even when the network has enough resources to provision and protect them by failing in finding arc-disjoint primary and backup paths.

For example, in Figure 6.2 (d), if we follow the algorithm described in Table 6.3, it is impossible to construct primary and backup paths. That is because if we attempt to find the shortest path from the source to the first destination "d_1" and from "d_1" to "d_2" using Step 2 (the algorithm is sequential and starts in an ordered manner with the first destination, then the second and so on.), we can never connect "d_2" to "d_3" and therefore we fail to find a primary path. To solve this problem, we propose an Optimized Collapsed Rings heuristic (OCR) that is described in detail in Table 6.4. The main difference between OCR and CR is that, in OCR, the first destination visited after the source is the closest destination to the source and not the first destination in the destination set. After that, the path is expanded to include the second closest destination and so on. Using the OCR heuristic, we are able to find arc-disjoint primary and backup paths for the multicast session in Figure 6.2 (d).

Table 6.4: Optimized Collapsed Rings Heuristic (OCR)

Step 1: Given a source "s" and multicast destinations $\{d_1, d_2, ...d_n\}$, form a ring set of vertices $\{v_1, v_2, ...v_n\}$, where v_1 is the source "s" and $v_2, ...v_n$ are the multicast destinations.
Step 2: For primary path, find the **closed destination** to the source using the shortest path algorithm, e.g. *d*, and remove all the links along the path. The new source is set to be *d*.
Step 3: Repeat **Step 2** until no more vertices are included in the ring set. This will form the primary path.
Step 4: For backup path, find the shortest path from source to the last destination in the primary path and traverse the primary path backwards until the first destination is reached.

6.4.3 Link-Disjoint Path Pair Protection (PP)

Another approach to provide pre-planned protection is to compute link-disjoint path pairs from a source node to all the destination nodes of a multicast session. This guarantees protecting the network against any fiber cut along the primary and the backup paths from the source to each destination. A path pair is said to be link-disjoint if the two paths do not share any links. Therefore, the link-disjoint path protection approach (PP) assures that each multicast destination can be reached from the source node by a link-disjoint path pair (i.e., primary and backup paths). The set of all the primary paths from the source to the multicast destinations form the primary multicast tree, while the set of all the backup paths form the backup multicast tree. Note that, a primary multicast tree can share links with the backup multicast tree as long as each destination can be reach by two link-disjoint paths. For example, in Figure 6.2 (e), we can see that the multicast session from source "s" to destinations $\{d_1, d_2, d_3\}$ is protected using the path protection approach. Link-disjoint path pairs for each destination are shown in the figure, for d_1, the primary path (s, a, d_1) and the backup path (s, b, d_1). On the other hand, for d_2, the primary path (s, a, d_2) and the backup path (s, b, d_3, d_2) and for d_3, the primary is $\{s, b, d_3\}$ and the backup is $\{s, a, d_2, d_3\}$. For all the three destinations, the primary paths are depicted in solid lines while the backup paths are depicted in dashed lines. Note that, the primary tree is formed by the primary paths for all the destinations, and the backup tree is formed by the backup paths. Finally, it is easy to verify that with appropriate switching at each node, the source node can deliver the bit streams to all the multicast destination nodes when any link failure occurs, even when a common link between the primary and the backup tree fails. This is because each destination is protected by link-disjoint path pair. For example, in

Figure 6.2 (e), if link (s-b) fails, a link that is shared by the primary and backup trees, the affected destination (d_3) can still receive the signal through the backup tree (branch {s, a, d_2, d_3}). As you can see from Figure 6.2 (e), this approach uses more links to set-up primary and backup trees than all other protection approaches, however, it guarantees a successful attempt to find the primary and backup trees (no blocking due to a failure of returning primary and backup trees since we can always calculate link-disjoint paths). The disadvantage of this approach is the extensive use of resources (more links, more resource usage).

6.4 Performance Evaluations

The performances of the proposed protection schemes were evaluated through the simulation of several network topologies that demonstrated similar conclusions. In this section, we present results for the 14 nodes, 21 links NSF network.

Unless otherwise specified, the following assumptions and parameters are used throughout the simulation:

- Each node in the network is an MC-OSW with full splitting capability, but with no wavelength conversion capability.
- Each adjacent node pair is interconnected by one (bi-directional) fiber and each fiber carries 64 wavelengths.
- Multicast traffic is assumed to constitute half of the total traffic and the other half is assumed unicast traffic.
- Signal power loss due to light splitting is neglected because optical amplifiers are used.

- A dynamic traffic model is used. Call requests arrive at each node according to a Poisson process and an arrival session is equally likely to be destined to any node(s) in the network.

Figure 6.3 shows the blocking probability performance of the different protection schemes for relatively low traffic load (10 Erlangs). Specifically, the proposed tree protection scheme using OSPT heuristic (TP-OSPT) outperforms all other schemes for large multicast group size.

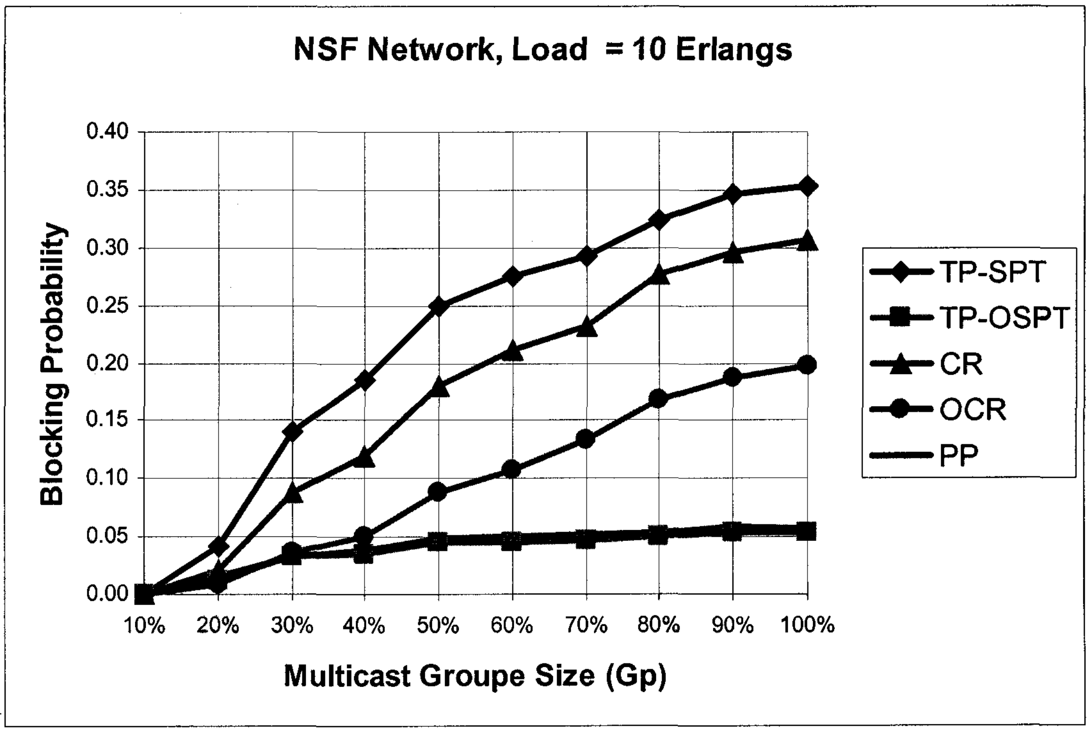

Figure 6.3: Blocking probability performance of the different protection schemes

In fact, as it is shown in Figure 6.3, when the multicast group size is less than 30%, the OCR scheme performs the best, and this is due to the fact that for small multicast group size, setting-up arc-disjoint routes requires less links for OCR. This is shown in Figure 6.4, where the average number of links used in the primary and backup routes/trees is calculated for TP-OSPT, OCR and PP protection schemes for small multicast group size (25%, i.e., maximum of 3 destinations for each multicast session). We can see clearly from the figure that, using the OCR scheme, calculating the primary and backup routes requires less links than TP-OSPT and PP (i.e., 8.21 for OCR comparing to 8.37 for TP-OSPT and 9.16 for PP). However, as can be seen in Figure 6.5, when the multicast group size is large (50%, i.e. maximum of 7 destinations for each multicast session), the TP-OSPT scheme requires fewer links to set-up primary and backup trees (i.e., 10.27).

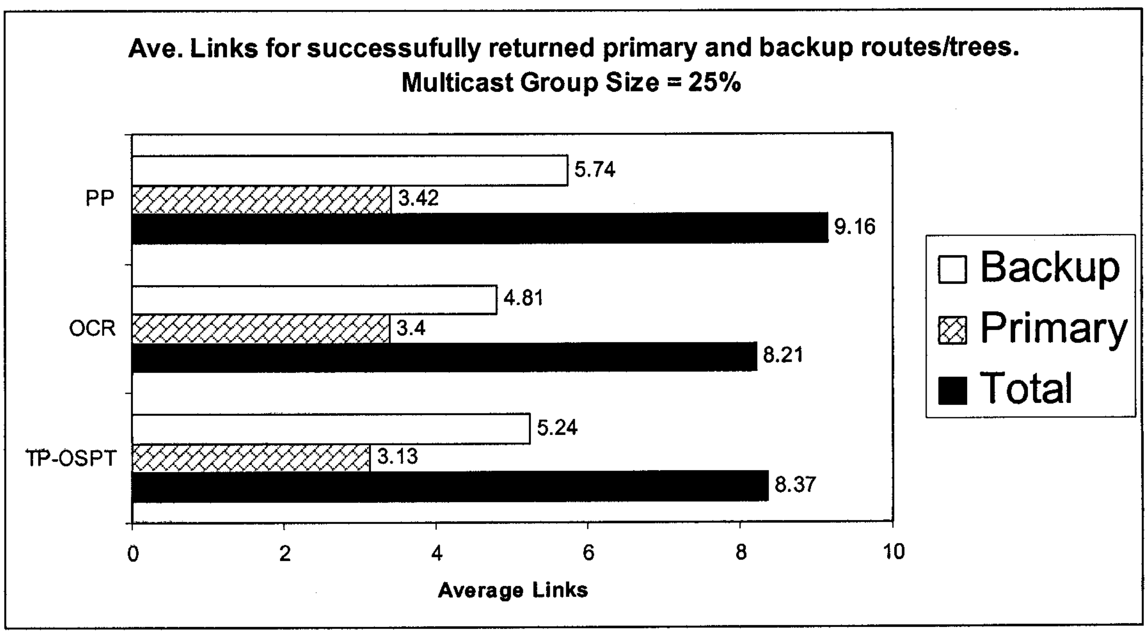

Figure 6.4: Average links used to set-up primary and backup routes/trees for small multicast group size

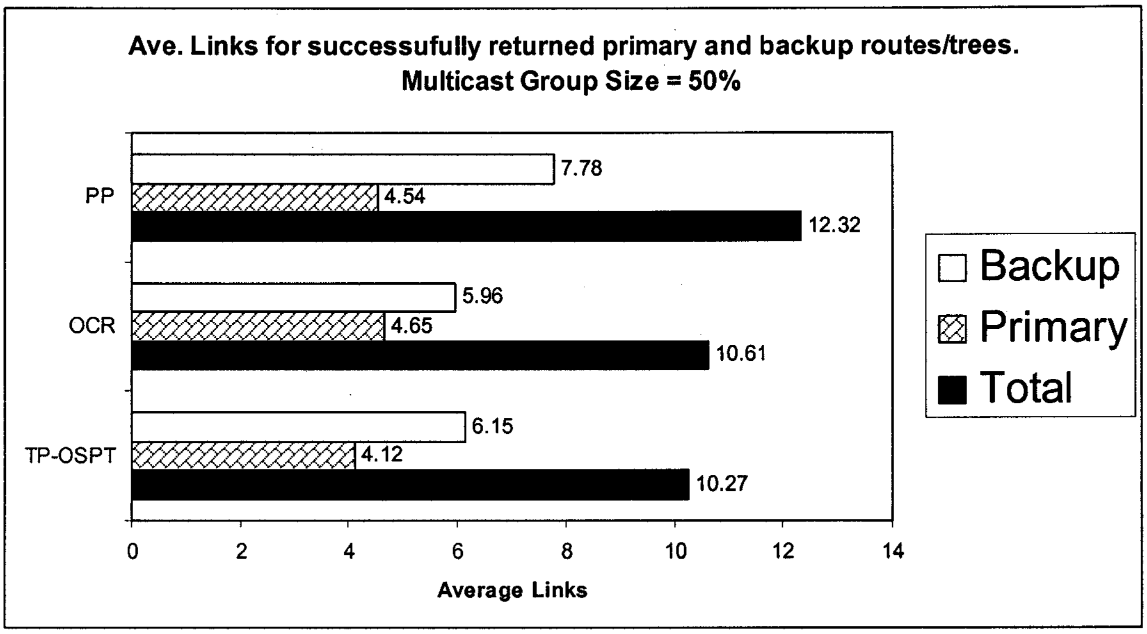

Figure 6.5: Average links used to set-up primary and backup routes/trees for moderate/large group size

We should also note that, as it was expected, the fact that PP scheme uses more links than OCR scheme to set-up primary and backup routes/trees affects the network performance only when the traffic load is high. In fact, in order to serve any unicast/multicast session, the routing algorithm should return valid primary and backup routes/trees and the network should have enough resources (i.e., available wavelengths along the routes/trees). Therefore, for low traffic load, when the network has enough available resources (i.e., 10 Erlangs), using longer routes/trees in the case of the PP schemes didn't affect much the blocking probability performance (Figure 6.3). As we mentioned before, PP scheme guarantees always finding primary and backup trees (even with larger average of used links), that means the blocking probability performance for this scheme is just affected by failing in finding enough resources. On the other hand, the blocking probability performance of OCR scheme is affected by failing in finding appropriate primary and backup arc-disjoint paths and the lack of network resources as well. Therefore, when the traffic load is high (i.e., not too many available wavelengths), the majority of the cases when the traffic is blocked is due to the lack of the enough network resources, not to the failure in finding primary and backup routes/trees. That means, using longer routes/trees in the case of PP scheme had negative effect on the network performance and lead to a higher blocking probability (this is due to the lack of available free wavelengths not to the failure of calculating the primary and backup routes/trees). This is depicted in Figure 6.6 when the blocking performance of TP-OSPT, OCR and PP schemes are calculated versus the multicast group size for high traffic load (i.e., 50 Erlangs). The figure shows that with the lack of the available resources, OCR outperforms PP; however, it is clear from the figure that when multicast group size is too large, once again, PP performs better than OCR.

6.5 Conclusions

This chapter has addressed the problem of dynamically provisioning survivable heterogeneous unicast and multicast connection requests in mesh-based WDM optical networks. The problem of finding link-disjoint route/trees depends on the heuristics used to find the multicast tree. The less optimum the heuristic, the more difficult is to find link-disjoint primary and backup trees. Several protection schemes have been proposed to solve this problem. Specifically, this work proposed new protection schemes that optimize the routing heuristics to provision survivable unicast/multicast connection requests in WDM-mesh networks. The simulation results of the proposed protection schemes were compared with each others and with those found in the literature. The results showed that our proposed scheme TP-OSPT outperformed all other schemes for moderate and large multicast group size. On the other hand, our proposed scheme OCR performed the best for small multicast group size.

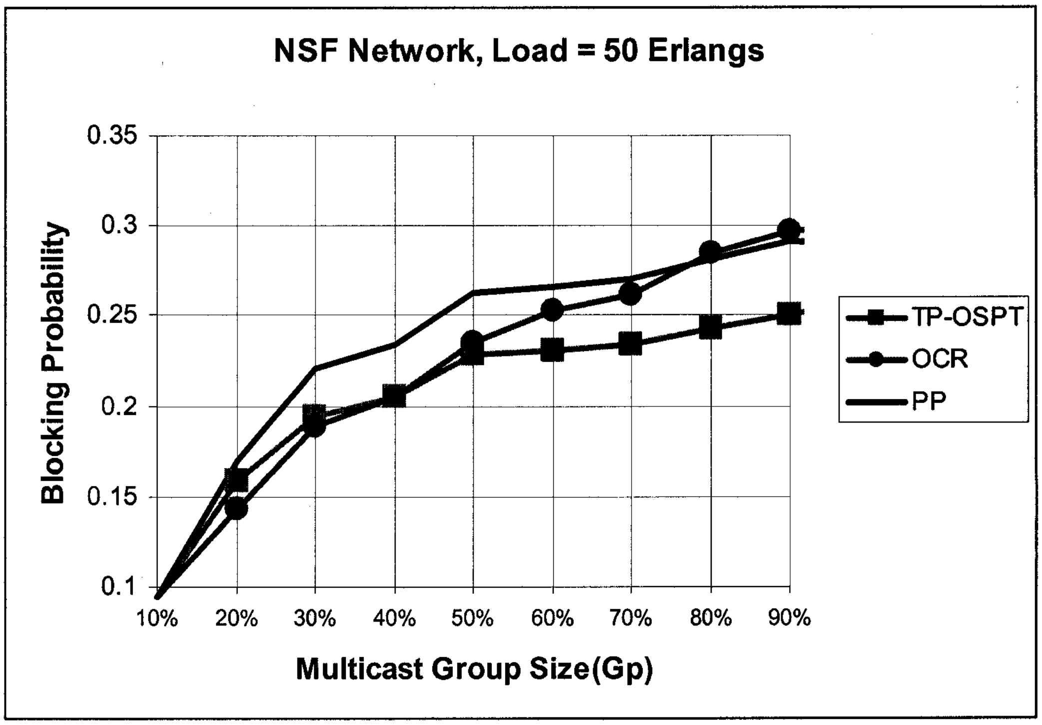

Figure 6.6: Effect of high load on the different approaches.

Chapter 7

7. Conclusions and Future Work

This thesis considered the problem of dynamically provisioning heterogeneous unicast/multicast traffic in next-generation IP-Centric WDM networks. Specifically, this work examined, through computer simulation and modeling, the technological requirements and assessed the performance analysis and feasibility for implementing next-generation data-centric optical networks capable of supporting real-time unicast as well as emerging multicast applications. Provisioning of either unicast or multicast connections requires algorithms for route (paths) selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route(s). This chapter summarizes the main results and contributions in this dissertation as well as outlines some of the future work.

7.1 Dynamic Real-Time Provisioning in Mesh-Based WDM Networks: Analytical Modeling

Real-time provisioning of optical channels has been presented in this chapter. Specifically, the work presented here has addressed provisioning of connections in a WDM based network, which is defined as the process of dynamically selecting efficient end-to-end routes and assigning wavelengths, i.e., routing and wavelength assignment (*RWA*). We analytically modeled the *RWA* problem with different wavelength assignment schemes. The analytical model is based on the layered-graph approach; it models the arrival rate as a Poisson distribution and utilizes the moment matching techniques to model the overflow traffic between different wavelength layers and between alternate routes. Different routing algorithms were studied and the blocking probability performance was computed and compared with those that use heuristics. We have also proposed the trunk reservation technique to improve the blocking performance for the fixed alternate routing (*FAR*) and investigated its effect on heavy-loaded and light-loaded network. *FAR* with/without trunk reservation (*TR*) is one approach to improve the network performance; analytical models for alternate routing without trunk reservation are also presented. We validated the accuracy of the proposed models through numerical comparison with simulation results of the *RWA*. We also showed the efficiency of alternate routing in improving the performance. However, as the traffic load increases, alternate routing degrades the blocking performance and the improvement of *FAR* is very limited; this is due to the fact that alternate routing will occupy more transmission resources and thus, at higher loads will prevent direct traffic from being routed and leads to instability. By limiting the flow of the alternately routed traffic, one can overcome the instability problem. Trunk reservation (*TR*) is one technique to improve the performance of alternate routing at higher loads and can better manage the network resources by selecting the right trunk threshold.

7.2 Unicast Traffic Grooming in IP/MPLS-over-WDM Networks

This chapter has proposed new dynamic algorithms for efficiently routing (i.e., grooming) low-speed traffic streams over high capacity lightpaths in IP/MPLS over WDM networks. Specifically, we proposed adaptive routing algorithms to dynamically route traffic flows over the logical topology, we compared their performance evaluations in term of call blocking rate with the conventional shortest path traffic-grooming algorithm approaches. Using a simulation study, we showed that there is a compromise between the number of logical hops and the logical route cost. Our results showed that the proposed dynamic *"Physical-First"* routing provided such a compromise and outperformed all other schemes.

7.3 Adaptive Integrated Routing Approach in Mesh-Based WDM Networks

This chapter has proposed and developed an adaptive integrated routing approach that takes into account the combined topology and resource usage information at both the IP and optical layers. Two different cost metrics have been developed and used to examine the performance of the proposed integrated routing approach. We have introduced tradeoff parameters to optimize the cost of logical and physical links in the network. This optimization technique, which has never been addressed in any previous work, allowed us to choose a dynamic cost function to efficiently use the network resources and obtain a near-optimal integrated routing. Instead of using an obvious/static cost function, we optimized the cost of the logical and physical links through simulation. This technique "guaranteed" an optimized route that uses efficiently the network resources under consideration without worrying about assuming "grooming policies" to efficiently use the network resources. Simulation results have shown that the proposed simple and scalable integrated routing approach outperforms the overlay sequential routing approaches. Furthermore, it has been shown that the link cost function (i.e., cost function Type 2) that minimizes pure physical provisioning and at the same time maximizes logical provisioning will always yield better routing performance. Finally, it is important to emphasize that other crucial performance metrics such as differentiated restoration algorithms and associated signaling protocols are beyond the scope of this thesis.

7.4 Dynamic Provisioning of Low-Speed Unicast and Multicast Traffic in Mesh-Based WDM Networks

This chapter addressed the problem of dynamically provisioning both low-speed unicast and multicast connection requests in mesh-based WDM optical networks. Several routing/provisioning schemes to dynamically provision multicast connection requests have been presented. We have devised a constraint-based grooming strategy to utilize the overall network resources as efficiently as possible. Based on this strategy, several different sequential multicast grooming heuristics have been developed. Guided by the simulation results of the sequential multicast grooming heuristics, we have augmented the sequential grooming heuristics by a hybrid approach to implement a grooming scheme that is biased toward serving multicast traffic demands in comparison with all other sequential grooming approaches.

Numerical results have indicated that the proposed grooming approaches use the network resources more efficiently compared to the non-grooming and unicast approaches. The results have also shown that the percentage of multicast sessions that are served on the logical topology using the hybrid scheme is always greater than that of the sequential approaches. This is very important because blocking a unicast session is usually less expensive than blocking a multicast session. Finally, the hybrid approach increased the percentage of both unicast and multicast calls that were served purely on the logical topology; hence, it minimized the total cost of the network by maximizing the utilization of the existent logical resources.

7.5 Dynamic Provisioning of Survivable Unicast and Multicast Traffic in Mesh-Based WDM Networks

This chapter has addressed the problem of dynamically provisioning survivable heterogeneous unicast and multicast connection requests in mesh-based WDM optical networks. The problem of finding link-disjoint route/trees depends on the heuristics used to find the multicast tree. The less optimum the heuristic, the more difficult is to find link-disjoint primary and backup trees. Several protection schemes have been proposed to solve this problem. Specifically, this work proposed new protection schemes that optimize the routing heuristics to provision survivable unicast and multicast connection requests in WDM-mesh networks. The simulation results of the proposed protection schemes were compared with each others and with those found in the literature. The results showed that our proposed scheme TP-OSPT outperforms all other schemes for moderate and large multicast group size. On the other hand, our proposed scheme OCR performed the best for small multicast group size.

7.6 Future Work

The thesis addressed a number of important issues, however several questions remain open. One area of research could be to study the effect of having full and sparse wavelength converters as well as sparse light splitters in mesh-based WDM networks with the presence of both unicast and multicast traffic. New algorithms could be developed based on the separation of the problem to two sub-problems, namely multicast routing sub-problem and wavelength assignment sub-problem.

Another area of interest is to extend the adaptive integrated routing approach proposed in chapter 4 to efficiently route unicast and multicast traffic demands. Specifically, it is very challenging to propose unified metrics that reflect the resource utilization (i.e. bandwidth, wavelength), as well as the traffic status in the network with the presence of unicast and multicast traffic demands that takes into account the combined topology and resource usage information at both the IP and optical layers.. The new algorithms and protocols could benefit from our results obtained in chapter 4 and extend the IP/MPLS-over-WDM networking paradigm that uses the network resources as efficiently as the peer model to support provisioning of diverse unicast and multicast traffic granularities, while still retaining the client/server relationship with the network and the simplicity of the optical UNI of the overlay architecture.

A third area of research could be finding an optimal solution as an alternative way to solve the problem of traffic grooming with unicast and multicast traffic demands addressed in this research work, where all the developed algorithms were evaluated via computer simulation on a custom-built C++ simulator. For example, an optimal Integer Linear Programming (ILP) formulation could be presented in order to optimize the network design for the unicast and multicast traffic grooming problem on random network topologies. Further more, different approaches (such as meta-heuristic approaches, i.e., Genetic Algorithm, Tabu Search) could be used to solve this problem and obtain a near optimal solution. These approaches will provide a solution that is very close to the optimal solution, while keeping the running times comparable to the ones obtained by the heuristic approaches. This direction of research will be a compromise between the optimal and practical solutions for large network topologies.

Publications

[1] A. Khalil et al. "Dynamic Provisioning of Survivable Heteregenous Unicast and Multicast Traffic in Mesh-Based WDM Optical Networks," *to be submitted for publication*

[2] A. Khalil et al. "Pre-Planned Multicast Protection Approaches in WDM Mesh Networks", *submitted for publication*

[3] A. Khalil et al. "Adaptive Integrated Routing Approach in WDM Networks," *submitted for publication*

[4] A. Hadjiantonis, A. Khalil, G. Ellinas, A. Shami, C. Assi and M. A. Ali, "An Integrated Routing and Signaling Framework for Dynamically Provisioning Diverse Traffic Granularity Entirely On The Optical Layer's Terms," *submitted for publication*

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[6] A. Khalil et al. "Dynamic Provisioning of Low-Speed Unicast and Multicast Traffic Demands in Mesh-Based WDM Optical Networks," *submitted for publication*

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Chapter 6

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