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Traffic Engineering in Hybrid, IP-Centric DWDM-Based Optical Networks

by

Abdallah Shami

A dissertation submitted to the Graduate Faculty in Engineering in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

The City University of New York

2003

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Abstract

TRAFFIC ENGINEERING IN HYBRID, IP-CENTRIC DWDM-BASED OPTICAL NETWORKS

By

Abdallah Shami

Adviser: Professor Mohamed A. Ali

This thesis considers the problem of real-time provisioning of optical channels in a hybrid IP-centric DWDM-based optical data networking. Provisioning of connections requires algorithms for route (path) selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. Specifically, this work addresses the implementation issues of both the path selection and signaling components of the traffic-engineering problem in such a network. Methodologies and associated algorithms for dynamic lightpath computation are devised and outlined.

This work has focused on developing and implementing comprehensive, unified constraint-based routing and signaling models and algorithms within the generalized MPLS framework (GMPLS), to provision full wavelengths. This is achieved through extending IP Multiprotocol Label Switching-based traffic engineering framework for provisioning, managing, and restoring switched lightpaths taking into account specific characteristics of optical-networking elements and special requirements of switched lightpaths.

During the first phase of this work, we have been addressing the implementation issues of the path selection component (first component) of the traffic-engineering problem in hybrid IP-centric DWDM-based optical networks. This work has presented and compared the performance of several different constraint-based routing and wavelength assignment algorithms for dynamic provisioning of the optical channels.

The second phase of this work has focused on implementing solutions for addressing the second component of the traffic-engineering problem: the signaling component that can reserve resources and establish path state in the network nodes selected by the route calculation process. Specifically, we have developed four different distributed signaling protocols for fast automatic setup and tear-down of paths across the emerging interconnection models for IP-over optical networks. The first scheme is flooding-based routing (FBR) algorithm with backward reservation while the second scheme is based on an adaptive routing algorithm called *Multi-Path Routing (MPR)* where k paths are probed simultaneously.

The third and fourth protocols are GMPLS-based distributed control and management protocols. The third protocol is a global information-based link state approach that consists of both an integrated RWA algorithm and a signaling algorithm. Two triggering mechanisms for the LSAs update procedures are considered: one is periodically-based and the other is threshold-based update. The fourth protocol is a local-information based fixed alternate link routing approach where the signaling protocol is closely integrated with the RWA protocols.

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Chapter 1

1. Introduction

1.1 Introduction

Recently, there has been a dramatic increase in data traffic, driven primarily by the explosive growth of the Internet as well as the proliferation of virtual private networks (VPNs). Traffic demand has increased substantially, somewhat unexpectedly, prompting carriers to add capacity quickly and in the most cost-effective way possible. Specifically, Internet Protocol (IP) applications are the fastest growing segment of a service provider's network traffic. This growth is expected to continue well into this century. This has led to a paradigm shift in the telecommunications industry from traditional voice-centric TDM/SONET (Time Division Multiplexing/Synchronous Optical Networks) circuit-switched to data-centric packet-switched networking.

Concurrently with the emerging data-centric networking paradigm, there has been a well-publicized “explosion” of attention centered on the topic of optical networking. With sky-rocketing optical networking startups, valuations, mergers, and acquisitions, the rest of the world has turned its attention to optical networking as the vehicle that promises to transform the Internet, blowing away bandwidth bottlenecks and almost eliminating delays. The myriad innovations in dense wavelength-division multiplexing (DWDM) technology that increase the number of wavelengths, generate more bandwidth,

send multi-gigabit signals faster and longer distances, and those enabling optical cross-connects (OXC) - with the ability to add, drop, and in effect construct wavelength-switched and wavelength-routed networks are moving us towards the vision of creating an all "Optical Internet" one that is free from all bandwidth and scalability restrictions, as well as distance limitations.

While the vision for creating such a "network of networks" seems to be gaining momentum, the implications of implementing this vision are far-reaching: all conventional aspects of networking functionality have to be reconsidered; the most basic assumptions of how networks are constructed are being called into question. At a minimum, service providers, carriers and enterprise network managers will be forced to fully rethink routing, switching, and traffic-engineering for the emerging data-centric networking paradigm.

Optical networking means many things to many people. It heralds a new economic era, when bandwidth will be abundant and inexpensive. But that's only the beginning. The real payoff comes when lightpaths (wavelengths) can be provisioned automatically. Dynamic wavelength provisioning, that is the focus of this thesis, will enable service providers to light up new connections faster than their competitors. Activation times will drop from months to minutes. Lambda-based traffic segregation will solve the quality of service (QoS) problem, and struggling applications like voice-over-IP (VOIP) will finally become practical. Together, automated provisioning and optical networking will open a whole new world of responsive, customer-driven services.

The fundamental idea is that the optical network infrastructure will represent an enormous, dynamic pool of bandwidth resources. With a hundred or more lambdas per fiber, dozens of fibers per conduit, and many conduits owned by many service providers, there will be many wavelength paths connecting endpoints in an optical network. With real-time signaling and dynamic routing, the optical network will be highly agile. Today's fixed circuit topologies are a thing of the past.

To better understand and appreciate the provisioning issue, we need to look into how circuits are provisioned in a typical network today. Provisioning a cross-country SONET service today requires several steps. First, connectivity from the customer premise to the carrier's POP must be established for each end of the circuit. Second, a physical path must be mapped out between the many physical hubs in carrier's network between the two points. Each path must be checked for fiber/ring bandwidth availability. Terminating equipment must be ordered and installed on each end of each fiber path. Each interconnect point must have capacity on the optical cross-connect system. All of the cross-connects and physical interconnects must then be made and each segment documented and tested. This process is extremely manual and generally takes several months to accomplish. DWDM complicates this process even further because tens and soon hundreds of wavelengths are support on individual fiber strands. Restoration in this type of network on dynamic routing over dynamic light paths will allow service providers to provision local and long distance connectivity across multiple physical fiber conduits in seconds, rather than the months required today.

Before this vision can be realized, however, networks need to slim down. 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 DWDM evolve, the ATM and SONET/SDH layers are becoming superfluous.

A simplified, two-tiered architecture that require two types of sub-systems will set the stage for a truly Optical Internet: service delivery platforms that enforce service policies; and transport platforms that intelligently deliver the necessary bandwidth to these service platforms. The solution, many believe, is to layer IP directly over the optical substrate. If IP can be mapped directly onto the WDM layer, some of the unnecessary network layers can be eliminated, opening up new possibilities for the potential of collapsing today's vertically layered network architecture into a horizontal model where all network elements work as peers to dynamically establish optical paths through the network. Reducing network overlay and eliminating SONET multiplexing and associated stand-alone NEs is also accompanied by removing SONET-layer bandwidth management and replacing it 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.

To bring IP and WDM together, new capabilities must be added to both. A framing standard is needed for carrying packets directly over lambdas. Signaling standards are needed so that IP devices can control optical resources. More importantly, with ATM and SONET out of the way, automated provisioning systems will gain direct access to WDM resources, and dynamic lightpath provisioning will become a strategic weapon for network service providers. Now that the basic building blocks are available for building such a “network of networks”, the key innovations will come from adding intelligence that enables the inter-working of all the network elements (Routers, ATM switches, WDM transmission systems and OXCs).

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 (MP λ S) 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.

What remains a major open issue is how the control plane for the optical domain should interact with the IP (or other client) control planes. In other words, how IP/MPLS routers must interact with optical core networks to achieve end-to-end connectivity. The Internet Drafts cited above describe several dynamic routing possibilities. The simplest is to treat the optical layer as completely separate from the IP layer. In this "overlay" model, optical transport offers only higher capacity and higher reliability. A more ambitious "integrated" model links the routing decisions at the IP layer with the dynamic reconfiguration capabilities of optical cross-connects (MP λ S). When routers detect a lot of traffic flowing on a multi-hop path, they could request a shortcut wavelength path to carry the traffic more efficiently.

1.2 Thesis Statement

This thesis considers the problem of real-time provisioning of optical channels in a hybrid IP-centric DWDM-based optical data networking. Provisioning of connections requires algorithms for route (path) selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. Specifically, this work addresses the implementation issues of both the path selection and signaling components of the traffic-engineering problem in such a network. Methodologies and associated algorithms for dynamic lightpath computation are devised and outlined.

This work focuses on developing and implementing comprehensive, unified constraint-based routing and signaling models and algorithms within the generalized MPLS framework (GMPLS), to provision a full range of bandwidth entities, e.g., packet flows, “sub-wavelength” and full wavelengths. This is achieved through extending IP Multiprotocol Label Switching-based traffic engineering framework for provisioning, managing, and restoring switched lightpaths taking into account specific characteristics of optical-networking elements and special requirements of switched lightpaths.

The problem of route selection in such wavelength-routed networks is referred to as the “routing and wavelength assignment (RWA) problem. The RWA problem consists of two sub-problems. The first is the routing problem, which determines the path along which the connection can be established. The second problem is to assign a wavelength (or a set of wavelengths) on each link along the selected path (wavelength assignment problem).

During the first phase of this work, we have been addressing the implementation issues of the path selection component (first component) of the traffic-engineering problem in hybrid IP-centric DWDM-based optical networks. Constrained-based optical path computation, is a special case of RWA algorithm. This work presents and compares the performance of several different constraint-based routing and wavelength assignment algorithms for dynamic provisioning of the optical channels. These schemes are based on fully distributed models, in which all optical nodes maintain a synchronized, and identical, topology and link state information base (traffic-engineering database, TED).

Specifically, unlike the conventional static RWA scheme used in most algorithms, which is often decoupled into the routing sub-problem and wavelength assignment sub-problem, the proposed algorithms integrate both the routing and wavelength assignment sub-problems into a single dynamic constraint-based routing problem. Thus, the emphasis here is on the adaptive routing problem, rather than focusing on the wavelength-assignment problem. It has been shown that the routing scheme has much more of an impact on the overall network performance than the wavelength-assignment scheme.

The second phase of this work focuses on implementing solutions for addressing the second component of the traffic-engineering problem: the signaling component that can reserve resources and establish path state in the network nodes selected by the route calculation process. Specifically, we have developed four different distributed signaling protocols for fast automatic setup and tear-down of paths across the emerging interconnection models for IP-over optical networks. The first scheme is flooding-based routing (FBR) algorithm with backward reservation while the second scheme is based on an adaptive routing algorithm called *Multi-Path Routing (MPR)* where k paths are probed simultaneously. Two path selection schemes are considered for the MPR approach, namely first come first serve (FCFS) path selection scheme and least-congested path (LCP) selection scheme. Our objective in developing these protocols is twofold: first, to avoid the implementation complexities associated with GMPLS-based CR-LDP and RSVP-TE signaling protocols; and second, to adapt the performance optimization algorithm to the requirements of different user applications by having the flexibility to

vary the relative weight assigned to each of three performance metrics [call acceptance rate (CAR), call set-up time (CST), and routing distance (RD)].

The main characteristic of the first two signaling schemes are: 1) the destination node makes adaptively both routing and wavelength selection decisions; 2) no global state information exchange among network nodes is needed for either scheme; 3) both schemes attempt to combine the benefits of both the conventional preferred neighbor (poor CST) and forward-based flooding (poor CAR) approaches in a way to improve all the three performance metrics simultaneously; 4) both schemes are able to achieve a lower CST and RD compared to that of CR-LDP, RSVP-TE, and the preferred neighbor due to their non-backtracking nature, since all/k paths are probed simultaneously; and 5) both schemes use backward-based reservation signaling to alleviate the excessive reservation of resources. This leads to a higher CAR.

The third and fourth protocols are GMPLS-based distributed control and management protocols. The third protocol is a global information-based link state approach that consists of both an integrated RWA algorithm and a signaling algorithm. Two triggering mechanisms for the LSAs update procedures are considered; one is periodically-based and the other is threshold-based update. The fourth protocol is a local-information based fixed alternate link routing approach where the signaling protocol is closely integrated with the RWA protocols. No update messages are required in this approach.

We present also a novel, fast, and distributed connection management protocol with rerouting capabilities for optical layer restoration in general mesh-type optical networks. We introduce a novel concept of a “token-based” distributed rerouting protocol to reroute existing connections to optimal paths after the failure recovery. The goal is to protect each connection from single-link failures, as well to minimize the overall blocking probability and the restoration delay. The performance of the proposed algorithms is evaluated and compared via simulation in a distributed control environment.

We employ both link-based and path-based restoration schemes to examine the applicability of the proposed approach over several performance metrics in a distributed environment. The traffic pattern considered here is dynamic where connection requests arrive one at a time and each connection exists for only a finite duration, called the connection-holding time. Given a fixed number of wavelengths on each fiber link, our objectives are: a) to minimize the overall call-blocking probability, b) to minimize the average end-to-end connection setup time, and c) to minimize the restoration delay after a link or node failure.

Finally, we present an original analysis of a Least-Loaded-Routing based rerouting scheme in wavelength-routed WDM networks. The proposed algorithm allows the redistribution of network loads for the relief of the congestion on direct paths. Through numerical examples and confirmation by computer simulation, the throughput of rerouting is established.

Chapter 2

2. Real Time Provisioning in IP-over-WDM Optical Networks

2.1 Introduction

Recently, there has been a dramatic increase in data traffic, driven primarily by the explosive growth of the Internet as well as the proliferation of virtual private networks (VPNs). At the same time, the rise of optical networking, first with wavelength-division multiplexing (WDM) transmission technology and more recently with optical multiplexers, and optical cross-connects (OXC) devices, is moving us towards the vision of creating an “all-optical” Internet. In particular, these technologies yield the ability to add, drop, and in effect construct wavelength-routed networks, heralding a new era in which bandwidth is relatively abundant and inexpensive. To some, a key realization of this vision will occur when lightpaths (wavelengths) can be provisioned automatically to create bandwidth between end-users, with timescales on the order of minutes or seconds. Dynamic wavelength provisioning is the main focus of this chapter, and will help open up a whole new world of responsive, customer-driven bandwidth services.

To better understand and appreciate the provisioning issue, we need to look into how circuits are provisioned in a typical network today. Provisioning a cross-country SONET

service today requires several steps. First, connectivity from the customer premise to the carrier's POP must be established for each end of the circuit. Second, a physical path must be mapped out between the many physical hubs in a carrier's network between the two points. Each path must be checked for fiber/ring bandwidth availability. Terminating equipment must be ordered and installed on each end of each fiber path, and each interconnect point must have capacity on the optical cross-connect system. All of the cross-connects and physical interconnects must then be made and each segment documented and tested. This process is extremely manual and generally takes several months to accomplish. WDM complicates this process even further because tens and soon hundreds of wavelengths are support on individual fiber strands. Clearly, an automated optical routing layer will facilitate much faster provisioning.

Before this vision can be realized, however, networks need to slim down. Today's core network architecture model has four layers: IP and other content-bearing traffic, over ATM for traffic-engineering, over SONET for transport, and over WDM for fiber capacity. This approach has significant functional overlap among its layers 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, a more efficient interworking is called for, i.e., one that exploits the complimentary features of each domain. In effect, high-performance routers plus a smart optical transport layer equipped with a new breed of photonic networking components and subsystems together are setting the foundation for the next-generation networking paradigm.

The solution, many believe, is to layer IP directly over the optical substrate [2]. If IP can be mapped directly onto the WDM layer, some of the functional overlap can be eliminated, potentially collapsing today's vertically layered network architecture into a horizontal model where all network elements work as peers to dynamically establish optical paths. To bring the IP and WDM layers together, however, new capabilities must be added to both layers. A framing standard is needed for carrying packets directly over lambdas. Signaling standards are needed so that IP devices can control optical resources [5]. More importantly, with the conventional multi layered architecture out of the way, automated provisioning systems will gain direct access to WDM resources, and dynamic lightpath provisioning will become easier and more practical to implement.

Once the view about network topology has changed, one will have to re-think routing as well. For example, initially, there was fixed routing over fixed circuits (PSTN), and next came dynamic routing over fixed circuits (IP). Subsequently, there was a move towards dynamic routing over virtual circuits (i.e., IP over ATM). Now, with recent advances in multi-protocol label switching (MPLS), we have label swapping over virtual circuits [3]. Furthermore, industry organizations like the Optical Internetworking Forum (OIF) and the Internet Engineering Task Force (IETF) are now extending MPLS-framework (Generalized-MPLS, also referred to as multi-protocol lambda switching, MP λ S) to support not only devices that perform packet switching (routers), but also those that perform switching in time (SONET), wavelength (OXC), and space. Therefore,

most likely the next evolution will be label swapping over dynamic circuits or lightpaths, see [4-11].

The Internet Drafts cited above describe several dynamic routing possibilities [7-11]. The simplest is to treat the optical layer as completely separate from the IP layer. In this "overlay" model, optical transport offers only higher capacity and higher reliability. A more ambitious "integrated" model links the routing decisions at the IP layer with the dynamic reconfiguration capabilities of optical cross-connects (MP λ S) [8]. The main goal of these initiatives is to provide a framework for real-time provisioning of optical channels, through combining recent advances in MPLS traffic-engineering control planes with emerging optical switching technologies in a hybrid IP-centric optical network [2].

This chapter considers the problem of real-time provisioning of optical channels in a hybrid IP-centric WDM-based networking model. Provisioning in this work implies that an optical channel is successfully routed if both an active path (working) and another alternate node/link-disjoint path (backup) are set up at the same time. Provisioning of connections requires algorithms for route selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. In particular, the problem of route selection in such wavelength-routed networks is referred to as the "routing and wavelength assignment (RWA) problem [13]. Here, we present a review of RWA schemes and also compare the performance of two different constraint-based routing/RWA algorithms for dynamic provisioning of the optical channels. Specifically, the RWA schemes are used to compute end-to-end dedicated and shared backup paths to

protect against single link/node failures. These algorithms are examples of approaches that might be used to simplify the complex problem of dynamic lightpath computation. Methodologies and associated algorithms for dynamic lightpath computation are outlined. We present an overview of the emerging architectural alternatives of the two-layer model, referred to in the literature as “the interconnection models”, for IP over optical networks, namely the overlay, the peer, and the augmented models [8]. Finally, we examine the implications of implementing the proposed RWA schemes for the lightpath provisioning aspects for each of the three emerging interconnection models.

The remainder of this paper is organized as follows. Section 2 presents an overview of the emerging architectural alternatives of the two-layer model. The proposed dynamic RWA algorithm is presented in Section 3. In Section 4, we present an overview of fault-tolerant routing. Section 5 presents the simulation results. The implementation of real-time provisioning at the optical layer is presented in section 6. Finally, Section 7 offers summary and conclusion.

2.2 IP over Optical Network Architectural Alternatives (Two-Layer Model)

In the network model considered here, clients (e. g., IP/MPLS routers) are attached to an optical core network, and connected to their peers over dynamically switched optical paths (lightpaths) spanning potentially multiple OXCs. The interaction between the client and the optical core is over a well-defined signaling and routing interface, referred to as the User-Network Interface (UNI). Meanwhile, the optical core

network consists of multiple OXCs interconnected by optical links in a general mesh topology. This network may be multi-vendor, where individual vendor OXCs constitutes sub-networks. Each sub-network itself is assumed to be mesh-connected. The interaction between the sub-networks is over a well-defined signaling and routing interface, referred to as the Network-Network Interface (NNI), see Figure 2.1.

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 is a fixed bandwidth connection between two network elements such as IP/ MPLS routers established via the OXCs. Two IP/MPLS routers are logically connected to each other by a single-hop channel. This logical channel is the so-called lightpath. A continuous lightpath is a path that uses the same wavelength on all links along the entire route from source-to-destination.

2.2.1 Interconnection Models

One approach for transporting IP traffic over WDM networks is to use a multi-layered architecture comprising of IP/MPLS layer over ATM over SONET over WDM. If an appropriate interface is designed to provide access to the optical network, multiple higher layer protocols can request lightpaths to peers connected across the optical network. This architecture has four management layers. Another approach is to use a packet over SONET approach, doing away with the ATM layer, by putting IP/PPP/HDLC into SONET framing. This architecture has three management layers. The

fact that both approaches support multiple protocols increases complexity for IP-WDM integration because of various edge- inter-workings required to route, map and protect client signals across WDM sub-networks [7].

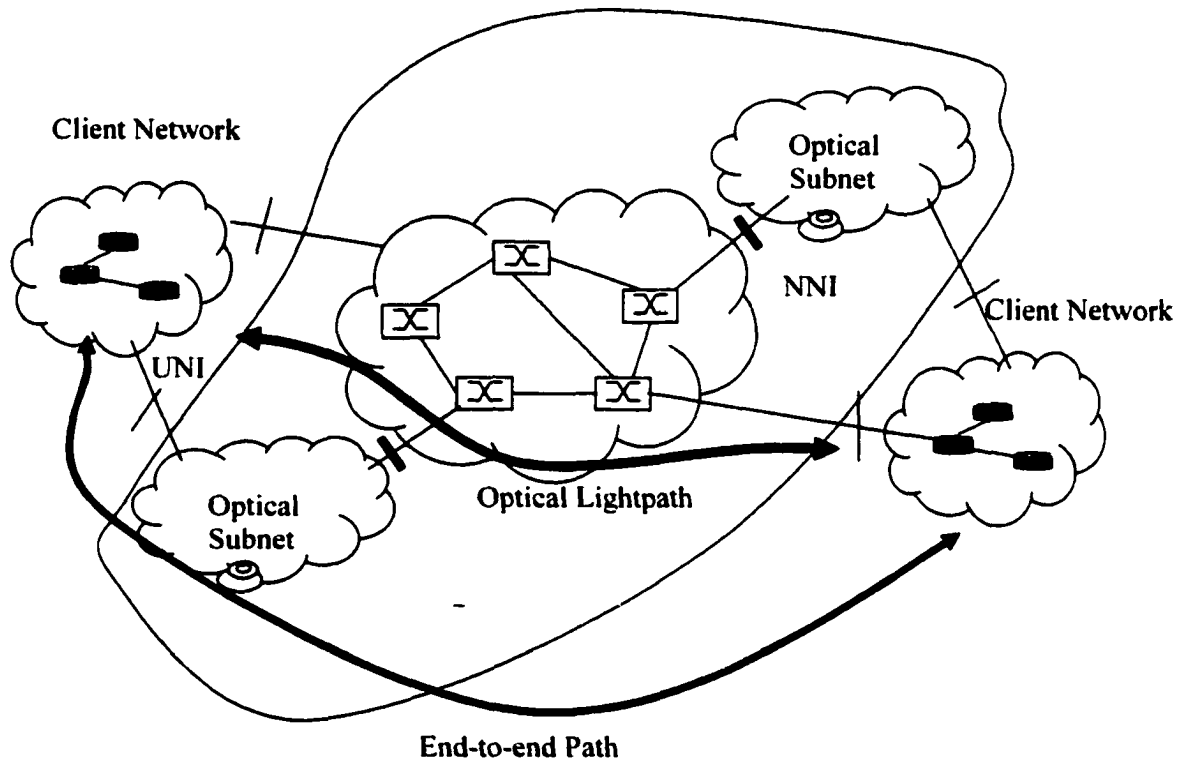


Figure 2.1: Optical Networking Model

The two-layer model, which aims at a tighter integration between IP and optical layers, offers a series of advantages over the current multi-layer architecture model. MPLS [3] and its extension G-MPLS [9] have been proposed as the integrating structure between IP and optical layers. Nevertheless, routing in non-optical and optical parts of hybrid IP

networks needs to be coordinated. To examine the architectural alternatives for the two-layer model (IP-over-optical network), it is important to distinguish between the data plane and control planes over the user-network interface (UNI). The IP-over-optical network architecture is classified according to the organization of the control plane, i. e., whether there is a single integrated or separate independent monolithic routing and signaling protocol spanning the IP and the optical domains. Several models have been proposed including overlay, augmented, and peer-to-peer models [8].

2.2.1.1 The Overlay Model

Under the overlay model, IP domain is more or less independent of the optical domain, that is IP domain acts as a client to the Optical domain. The IP/MPLS routing and signaling protocols are independent of the routing and signaling protocols of the optical layer. Thus, the topology distribution, path computation, and signaling protocols would have to be defined for the optical domain. In this model, the client routers request high-bandwidth connections (lightpaths) from the optical network through the UNI. The client routers are provided with no knowledge of the optical network topology or resources. In this scenario, the optical network provides point-to-point connection to the IP domain. The overlay model may be statically provisioned using a network management system or may be dynamically provisioned.

2.2.1.2 The Peer Model

In the peer model, the two layers are collapsed into a single integrated layer managed and traffic engineered in a unified manner. In this regard, the OXCs are treated just like any other router (IP/ MPLS routers and OXCs act as peers) and there is only a single instance of a routing protocol spanning an administrative domain consisting of the core optical network and the surrounding edge devices (IP/MPLS routers, ATM switches). Thus, from a routing and signaling point of view, there is no distinction between the UNI, the NNI (network-network-interface), and any other router-to-router interface. This allows the SP edge devices to have a full access to the topology of the core network. A common IGP like OSPF or IS-IS may be used to exchange topology information. The assumption in this model is that all the optical switches and the routers have a common addressing scheme.

2.2.1.3 The Augmented Model

In the augmented model, the IP and optical domains can be functionally separated, each running its own routing protocol, but exchanging full reachability information across the UNI using a standard protocol. For example IP addresses could be assigned to optical network elements and carried by optical routing protocols to allow reachability information to be shared with the IP domain to support some degree of automated discovery. This model combines the best of the peer and overlay interconnection models; it is relatively easy to deploy compared to the peer model in the near term. Also, this is a convenient solution, since it allows implementation of both provisioning and restoration procedures for optical sub-networks independent of the

client network routing. In addition, this approach supports the common scenario where the optical network and client networks are administered by different entities.

The central issue in this model is how the routing information is exchanged at the IP-optical UNI. There are two possibilities for this. The first is to consider the interdomain IP routing protocol, BGP, which may be adopted for exchanging routing information between IP and optical domains. The second is to consider the use OSPF areas (OSPF supports a two-level hierarchical routing scheme through the use of OSPF areas) to exchange routing information across the two domains [12]. On the other hand, running a protocol like BGP across the UNI may be considered too involved, at least for initial implementations of the UNI. A simpler approach would be to limit the reachability information passed through the optical network [12].

2.3 Dynamic RWA

Provisioning of connections requires algorithms for route selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. The problem of route selection in such wavelength-routed networks is referred to as the “routing and wavelength assignment (RWA) problem”, and consists of two sub-problems. The first is the routing problem, which determines the path along which the connection can be established. The second problem is to assign a wavelength (or a set of wavelengths) on each link along the selected path (wavelength assignment problem). Real-time provisioning implies that both the path and wavelength should be

chosen/assigned dynamically (dynamic RWA), depending on the network state. In general, all networking models described above, regardless, require route/wavelength computation/assignment to provision a lightpath, i. e., dynamic RWA engine.

2.3.1 Overview of the RWA Problem

Given a set of connections, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called the routing and wavelength assignment (RWA) problem [13]. Typically, connection requests may be of three types: static, incremental and dynamic [14]. With static traffic, the entire set of connections is known in advance, and the problem is then to set up lightpaths in a global fashion while minimizing network resources such as the number of wavelengths or the number of fibers in the network. Here, the RWA problem for static traffic is known as Static Lightpath Establishment (SLE) and can be formulated as mixed-integer linear program [15]. In the incremental-traffic case, connection requests arrive sequentially, a lightpath is established for each connection, and the lightpath remains in the network indefinitely.

For the case of dynamic traffic, a lightpath is setup for each connection request as it arrives, and the lightpath is released after some finite amount of time. The objective in the incremental and dynamic traffic cases is to setup lightpaths and assign wavelengths in a manner that minimizes the amount of connection blocking [14]. This problem is referred to as the Dynamic Lightpath Establishment (DLE). Generally, the DLE is more

difficult to solve, and therefore, heuristics methods are generally employed. Heuristics exist for both the routing sub-problem and the wavelength assignment sub-problem.

For the routing sub-problem, there are three basic approaches that can be found in the literature: fixed routing, fixed-alternate routing, and adaptive routing [14]. Fixed routing is one variant of the “static routing” in which routing decisions do not vary with time. Moreover, in fixed routing the same fixed route for a given source-destination pair is always selected. The fixed alternate routing approach considers multiple routes between a source-destination pair and each node in the network maintains an ordered list of a number of fixed routes to each destination node. When a connection request arrives, the source node attempts to establish the connection on each of the routes from the list in sequence, until a route with a valid wavelength assignment is found. Conversely, in adaptive routing [14, 16, 17, 18], the route from a source node to a destination node is chosen dynamically, depending on the network state. Adaptive routing requires extensive support from the control and management protocols to continuously update the routing table at the node. An advantage of adaptive routing is that it results in lower connection blocking than fixed and fixed-alternate routing.

Meanwhile, for the wavelength assignment sub-problem, a number of heuristics have been proposed [19, 20, 21]. These heuristics are Random Wavelength Assignment, First-Fit, Least-Used, Most-Used, Min-Product, Least-Loaded, MAX-SUM, Relative Capacity Loss, Wavelength Reservation, and Protecting Threshold. In [17], the authors propose an

adaptive unconstrained routing (AUR), which incorporates network state information into route computation and channel allocation.

Currently, The algorithms that offer the best performance are Relative Capacity Loss (RCL) [21], and Distributed relative Capacity Loss (DRCL) [14]. RCL calculates the Relative Capacity Loss for each path on each available wavelength and then chooses the wavelength that minimizes the sum of the relative capacity loss on all the paths. DRCL is proposed in [14] and is based on RCL but it is more efficient in a distributed environment. For a tutorial review on the RWA problem, we refer the reader to [14].

Optical networks can also pose added wavelength continuity constraints [13], and these may require the use of wavelength conversion (also referred to as wavelength translation or wavelength changing). A wavelength converter is a device, which takes at its input a data channel modulated onto an optical carrier with a wavelength λ_m , and produces at its output the same data channel modulated onto an optical carrier with a different wavelength λ_{out} . If wavelength converters are included in the OXCs in WDM networks, connections can be established without the need to find an unoccupied wavelength, which is the same on all the links making the route. This means that networks with wavelength converters are equivalent to traditional circuit switched networks. Wavelength converters thus result in improvements in network performance. On the other hand, it has been shown that a careful wavelength assignment in wavelength-continuous network can lead to improved performance; thus, reducing the benefits of wavelength converters [22]. In [22], the authors investigate the benefits of

limited wavelength conversion for ring and mesh-torus topologies with fixed shortest path routing. The authors of [23] used a hypercube network to study limited conversion with fixed shortest path routing and a first-fit wavelength selection algorithm. It is shown that limited wavelength conversion (25 %) achieves the same performance improvement as full wavelength conversion [22,23].

Additionally, many other constraints can also serve to complicate the RWA process, especially in all-optical networks. Specifically, besides wavelength continuity requirements, these include analog attenuation effects and power limitations. For example, adequate signal-to-noise ratios (SNRs), crosstalk, and dispersion effects caused by subsystem components and fiber links can be computed along candidate paths. This information can be incorporated into route resolution strategies by defining new cost functions [24]. In [24], the authors have extended the routing and wavelength assignment problem to account for the power degradation of a routed signal due to non-ideal behavior of optical components such as multiplexers, demultiplexers, taps, and fiber links.

2.3.2 The Proposed Dynamic RWA Algorithms

Some combined RWA algorithms are now presented. Specifically, these algorithms integrate and collapse both the routing and wavelength assignment sub-problems into a single dynamic constraint-based routing problem. Thus, the emphasis here is on the adaptive routing problem, rather than focusing on the wavelength-

assignment problem. It has been shown that the routing scheme has much more of an impact on the overall network performance than the wavelength-assignment scheme [14,16]. Moreover, both algorithms are also shown to be capable of supporting fault-tolerant adaptive routing and are amenable to fully distributed implementations.

The network is viewed as a multi-layered graphs each corresponding to a specific wavelength. For a connection request and on a given wavelength, Dijkstra's shortest path algorithm, that is suitably modified for WDM networks, is used for computing a constraint path. 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 wavelengths [18]. This means that the algorithm might compute (on-line) W Paths, each corresponding to one of the W wavelengths. Then, one of these paths is selected according to a global selection criterion. Thus, the problem of wavelength-assignment is totally mitigated and both the routing and wavelength assignment sub-problems are now integrated and collapsed into a single dynamic constraint-based routing problem. This in contrast to the work reported in [18], where a single path is first calculated; then a wavelength is assigned to the path by propagating a wavelength request to all the routers along the path. Thus, such algorithm avoids the overhead associated with such a wavelength request (probe message). The emphasis here is on the adaptive routing problem, rather than focusing on the wavelength-assignment problem. It has been shown that the routing scheme has much more of an impact on the overall network performance than the wavelength-assignment scheme [14-16].

The algorithm is implemented as per the following:

1. First consider a multi-fiber IP-centric WDM-based network whose physical topology consists of multiple OXC interconnected via point-to-point WDM links in an arbitrary mesh topology.
2. Assume that none of the OXCs has wavelength conversion capability. Hence, to meet a connection request, a lightpath, that uses the same wavelength on all the links along the entire route from source-to-destination, has to be set up.
3. Both algorithms are based on a fully distributed implementation in which all nodes maintain a synchronized and identical topology and link state information (traffic-engineering database, TED).
4. Assuming that W is the number of wavelengths per fiber, the network is represented by W identical graphs, each conforming to the physical topology and a particular wavelength. Hence, the network can be viewed as W identical wavelength graphs, each representing a wavelength. In view of this multi-graph model, each physical link is now represented by W virtual links (channels), each corresponding to one of the wavelength graphs. Figure 2.2 illustrates the concept of the multi-graph approach for a simple network with four nodes, four physical links, and $W = 2$.

5. For a given connection request, a constraint route is calculated, for each of the wavelength graph, throughout the entire network from source to destination, typically using a shortest path algorithm but with the link weights adjusted to attain some sort of local resource optimization. Clearly, there are at most W paths that can be calculated, each corresponding to a given wavelength, provided that each path can meet the given routing constraint. As a result, we get the vector $V = \langle \text{Path}_i, \text{Wavelength}_i \rangle, i = 1, \dots, W$, where the number of entries stored in V may vary from no entries at all (request is blocked), to a possible maximum of W entries. Finally, to globally optimize the network resources, provided that the number of entries stored in V is more than one, an entry $(\text{Path}_i, \text{Wavelength}_i)$ out of all the other possible entries, has to be selected. Thus, by virtually separating wavelengths, both the routing and wavelength assignment sub-problems are now reduced into a single dynamic constraint-based routing problem.

2.3.2.1 Algorithm I “Full Adaptive Routing”

The implementation of this algorithm is as follows:

1. For a given wavelength graph λ_i , each virtual link, in each of the W wavelength graphs, is assigned a cost. Basically, the cost of a link at a given wavelength λ_i , is defined here as the inverse of the number of available channels over that particular link. Hence, initially the cost of a given link throughout the entire network is set =

(1/F), where F is the number of fibers (per link) connecting two adjacent OXCs. In general, the cost of link L_j at wavelength λ_i , $C(L_j^{\lambda_i})$, is given by:

$$C(L_j^{\lambda_i}) = \begin{cases} \frac{1}{F - N(L_j^{\lambda_i})} & \text{if } N(L_j^{\lambda_i}) < |F| \\ \infty & \text{if } N(L_j^{\lambda_i}) = |F| \end{cases} \quad (1)$$

Where $N(L_j^{\lambda_i})$ is the number of occupied (unavailable) λ_i 's on link L_j .

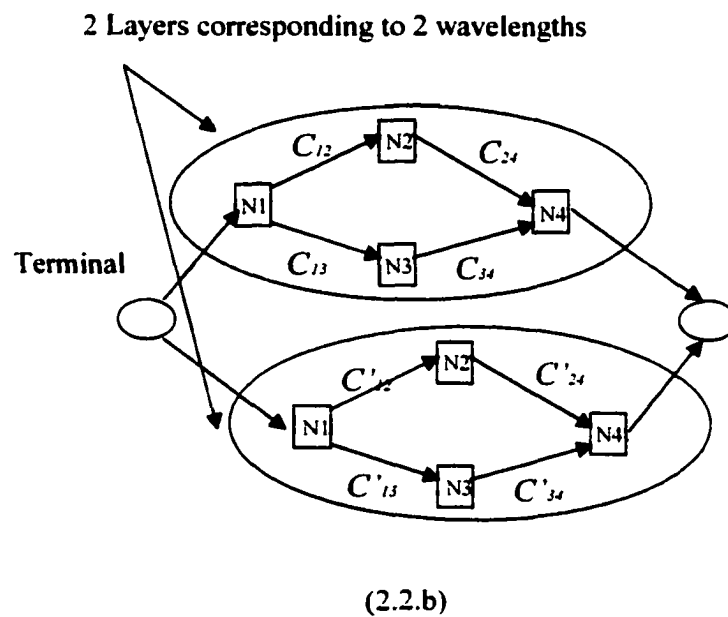
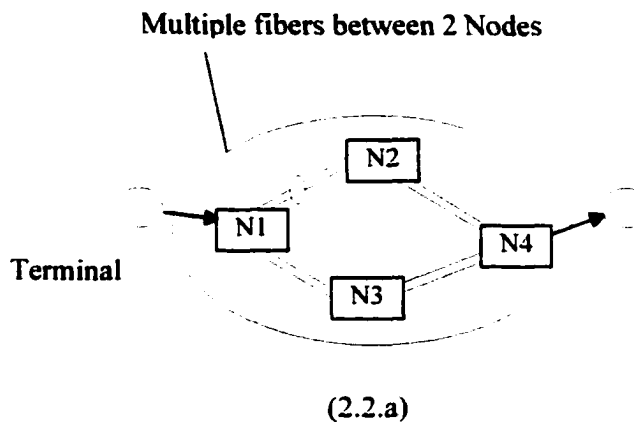


Figure 2.2: The sample network model (2.2.a) . and its multi-layered graph approach(2.2.b).

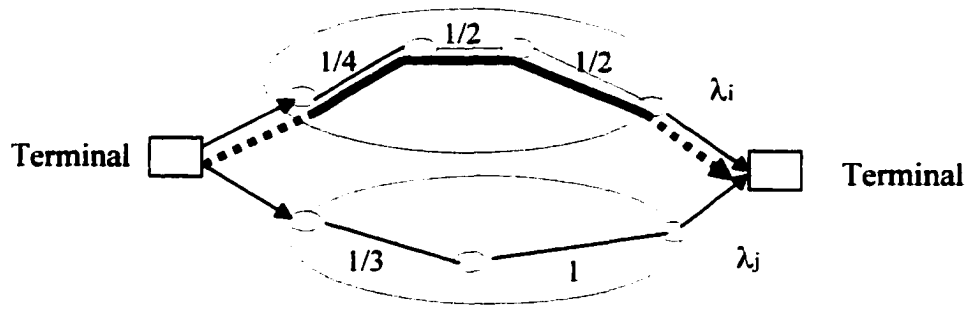


Figure 2.3.a (Total Cost Path Selection, λ_i)

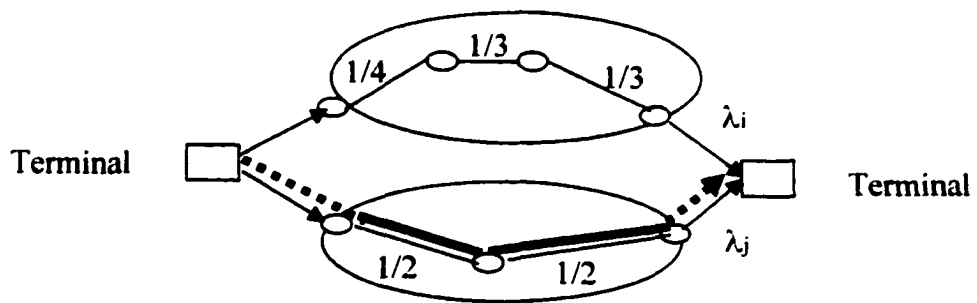


Figure 2.3.b (Balanced Cost Path Selection, λ_j)

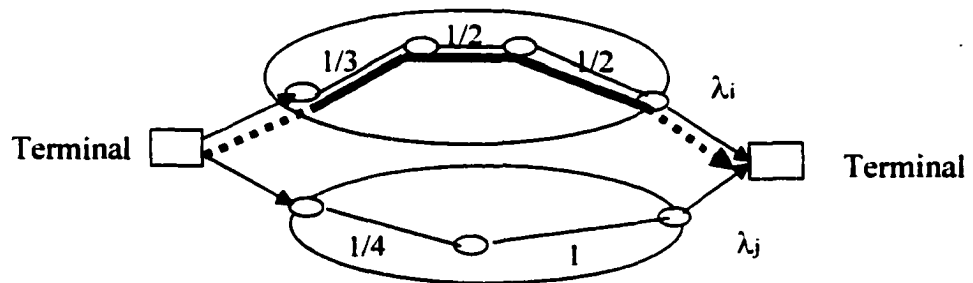


Figure 2.3.c (Future Cost Path Selection, λ_i)

Figure 2.3 Illustration Examples

2. For a given wavelength λ_i , we associate each path throughout the entire network with a total cost, $C_{sd}^{\lambda_i}$, which is defined here as the summation of the costs of all individual links spanning the entire path from source to destination.

$$C_{sd}^{\lambda_i} = \sum_{j=1}^n C(L_j^{\lambda_i}) \quad (2)$$

Where $\langle L_1, L_2, \dots, L_n \rangle$ is the set of n links that comprise the path.

3. For a given connection request, run the Dijkstra's algorithm on the first wavelength graph λ_1 to find the shortest path (the path with minimum $C_{sd}^{\lambda_i}$). Store the calculated path along with its corresponding wavelength λ_1 as the first entry of the vector V . Note that the calculated local path, for a given wavelength graph λ_i , is not necessarily the path with the minimum number of hops.
4. Repeat step 3 for each of the remaining $W-1$ wavelength graphs. Note that the vector V might have now up to W entries.
5. Examine the contents of the vector V and perform one of the following instructions:
- If the vector V has no entries at all, reject the connection request; otherwise go to step # b.
 - If the vector V has only one entry, select this entry as the combination (Path _{i} , Wavelength _{i}) that satisfies the connection request. After assigning the path,

update the weights associated with all links along the entire path (just on the corresponding wavelength graph λ_i) by basically decrementing the number of the available λ_i 's (channels), on every link along the selected path, by one; otherwise go step # c.

- c) If the vector V has more than one entry, select one of the those entries combination that satisfy one of the following global path selection schemes:

I. Total Cost-Based selection

In this scheme, a total cost, $C_{sd}^{\lambda_i}$, is associated with each computed path within the vector V ($\langle \text{Path}_i, \text{Wavelength}_i \rangle$), given by:

$$C_{sd}^{\lambda_i} = \sum_{j=1}^n C(L_j^{\lambda_i}) \quad (3)$$

The path with the minimum total cost $C_{sd}^{\lambda_i}$ is selected and assigned to the connection.

Note that this selection criterion skews the conventional shortest path search to favor less utilized network resources. This is illustrated in Figure 2.3.a where the path with fewer hops is not selected.

II. Balanced Cost-Based selection

In this case, each path is assigned a balanced cost, $C_{sd}^{B\lambda_i}$, defined by:

$$C^{B}_{sd}{}^{\lambda_i} = n \times \left(\sum_{j=1}^n C_{L_j}{}^{\lambda_i} \right)$$

Where n is the total number of links along the path.

The path with the least balanced cost $C^{B}_{sd}{}^{\lambda_i}$ is selected and assigned to the connection. Note that this selection criterion strikes a balance between the minimum cost and the minimum number of hops. The main objective of this selection criterion is to avoid assigning long paths to a connection and route connections over the healthy part of the network. This is illustrated in Figure 2.3.b where the connection is routed here on the path with wavelength λ_j that has a balanced cost ($2*1$) less than that with wavelength λ_i [$3*(11/12)$], thus avoiding assigning the connection to the longer path (λ_i). Note, however, that the total cost of the path with wavelength λ_j (1) is higher than that with λ_i (11/12).

III. Future Cost-Based selection

This scheme uses the same total cost $C^{B}_{sd}{}^{\lambda_i}$ of Eq. (3), but with the individual link cost $C_{L_j}{}^{\lambda_i}$ of Eq. (1) redefined as:

$$C(L_j{}^{\lambda_i, Future}) = \frac{1}{F - 1 - N(L_j{}^{\lambda_i})} \quad \text{if } N(L_j{}^{\lambda_i}) < |F|$$

Thus, the total future cost of this scheme is given by:

2.3.2.2 Algorithm II “Semi-Adaptive Routing”

This algorithm adopts the same implementation procedures developed for the full adaptive algorithm described above, except for the following fundamental differences:

1. A shortest path algorithm (Dijkstra’s algorithm) is initially run off-line to calculate the shortest path (just minimum number of hops) between every source-destination node pair (routing tables) throughout the entire network. These off-line computed routing tables are stored at each node in every wavelength graph. Thus, the initial routing tables are identical for all W wavelength graphs.
2. For an initial connection request, the ingress node at every wavelength graph consults its own routing table for the shortest path. As a result, similar to algorithm I, we may get as much as W paths, where one of them can then be selected according to the selection schemes described above.
3. For all the consecutive connection requests, the routing tables remain unchanged; so that step 2 is repeated until the cost of a link L_j in a given wavelength graph λ_i goes to infinity (no more available λ_i ’s). In this case, link L_j is removed from wavelength graph λ_i and the routing tables are calculated for each node again. Note that the Dijkstra’s algorithm is run this time on-line to find the shortest path (the path with minimum $C_{sd}^{\lambda_i}$).

Note that the signaling overhead associated with the link state updates for this algorithm is considerably less than that of algorithm I (link state updates is only triggered when the cost of the link goes to infinity). In addition, the time associated with computing a path for the semi-adaptive algorithm is less than that of the full adaptive one, since the path is directly read of the routing table.

Finally, in the case where the lightpath is wavelength continuous as this work has assumed, optical non-linearities, chromatic dispersion, amplifier spontaneous emission and other factors together limit the scalability of an all-optical network. Routing in such networks will then have to take into account noise accumulation and dispersion to ensure that lightpaths are established with adequate signal qualities. This work assume that the all-optical (sub-) network considered is geographically constrained so that all routes will have adequate signal quality, and physical layer attributes can be ignored during routing and wavelength assignment. However, the policies and mechanisms proposed here can be extended to account for physical layer characteristics, and requires future work.

2.4. Fault-Tolerant Routing

Given the wide range of services envisioned for future IP networks, network survivability is a crucial concern. Survivability schemes can be classified into two forms, protection and restoration, where the former refers to pre-provisioned failure recovery and the latter refers to more dynamic signaled recovery [2]. A common approach to protection is to setup two physically link-disjoint paths for every connection request. One

path, called the primary, is used to transmit data, while the other path is reserved as a backup in the event that a link in the primary path fails. To further protect against node failures, the primary and backup paths may also be node-disjoint [25,26].

Fixed-alternate routing provides a straightforward approach to handling protection [17]. On the other hand, in adaptive routing, a protection scheme may be implemented in which the backup path is setup immediately after the primary path has been established [14]. The same routing protocol may be used to determine the backup path with the exception that a link cost is set to infinity if that link is being used by the primary. The resulting route will then be link-disjoint from the primary path. Since these schemes require backup path routing at setup time, they must be more closely incorporated with the primary lightpath RWA algorithms. On the other hand, channel restoration does not rely on pre-computed backup routes, and instead dynamically re-computes a new path for a broken channel [26]. This has the advantage of low overhead in the absence of failures. However; this does not guarantee successful recovery, since the attempt to establish a new path may fail due to resource shortage at the time of failure recovery. Additionally, recovery timescales are usually longer [2].

By making use of the WDM channel routing capabilities, a variety of lightpath protection schemes can be designed. For example, dedicated backup channels can be provisioned for users requiring high availability. Here, a pre-computed link-disjoint backup channel is reserved for each primary channel at setup time, and in case of a fault condition on the primary path, a channel switchover is performed. The dedicated backup reservation method has the advantage of shorter restoration time since the resources are

reserved for the backup path when establishing the primary path itself. However, this method reserves excessive resources. For better resource utilization, multiplexing techniques [28] can be employed. If two primary lightpaths do not fail simultaneously, their backup lightpaths can share a wavelength channel. However, in case of primary link failure, the backup capability of the other is no longer preserved. Therefore, although channel-blocking rates will be less (than the dedicated case), channel recovery probability will be also lower.

In addition, recently the concept of a shared risk link group (SRLG) definition has also been proposed to help identify risk associations between various entities, see [29]. This concept is used to ensure that the primary and the backup path are not affected by the same failure. By using this concept, adequate resource "disjointness" can be introduced into the constraint-based path computation phase, thereby reducing the probability of simultaneous lightpath failures (e.g., between working and protection paths). Further details are out of the scope herein and interested readers are referred to [8, 29].

Overall, the proposed adaptive RWA scheme can be extended to ensure diversity in routes. This can be achieved by coordinating each diversely routed lightpath group by a single network entity. To create a diversely routed lightpath group, a user registers with a coordinator, and receives the group identifier. For groups originating through the same client router, this router would typically act as the coordinator. To ensure diversity in

routes, N SRLG and node disjoint routes through the network are selected, where N represents the number of diverse routes required.

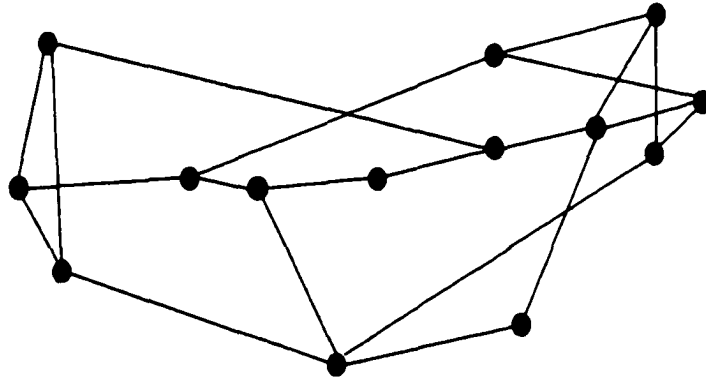


Figure 2.4: 14-node NSFNET topology

2.5 Simulation Results

The performance of the proposed dynamic RWA algorithms is evaluated via simulation of the mesh-based NSFNET shown in Figure 2.4. The NSFNET consists of 14 nodes and 21 physical links. Each adjacent node pair is connected through a bi-directional physical link that consists of N fibers, where each fiber is assumed to have the same number of wavelengths (W). The simulation results calculated in this section assumes that $N = 2$ and $W = 4$. 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. If at any time, a connection request cannot be satisfied according to the algorithms developed above, the connection request is dropped.

Fig. 2.5 shows the simulated blocking probability vs. the calls arrival rate for both algorithms when the total cost-based path selection criterion (scheme I) is used. The simulated blocking probability is also shown in the figure for the conventional static RWA scheme used in most algorithms. As expected, it can be seen from the Figure, the performance of both dynamic algorithms is significantly better than that of the static one. Note, however, that the performance of the full-adaptive algorithm is slightly better than that of the semi-adaptive. These results always hold, independent of which path selection scheme described above (I, or II, or III) is used.

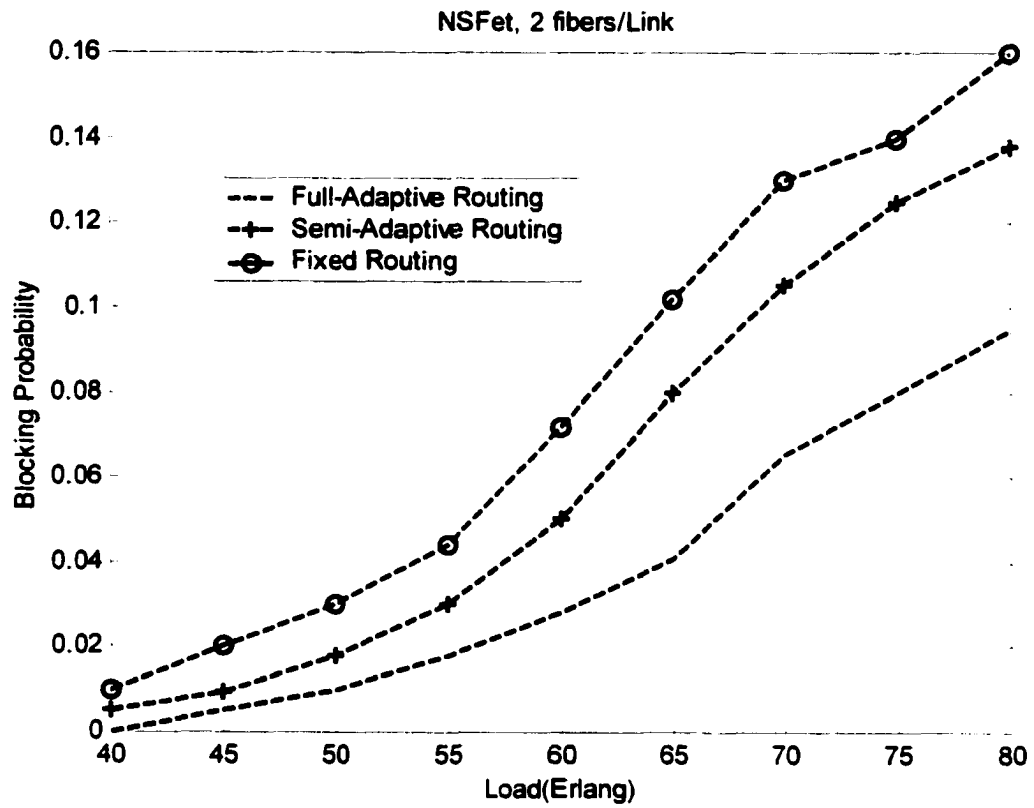


Figure 2.5 Blocking probability vs. Load, for different routing schemes

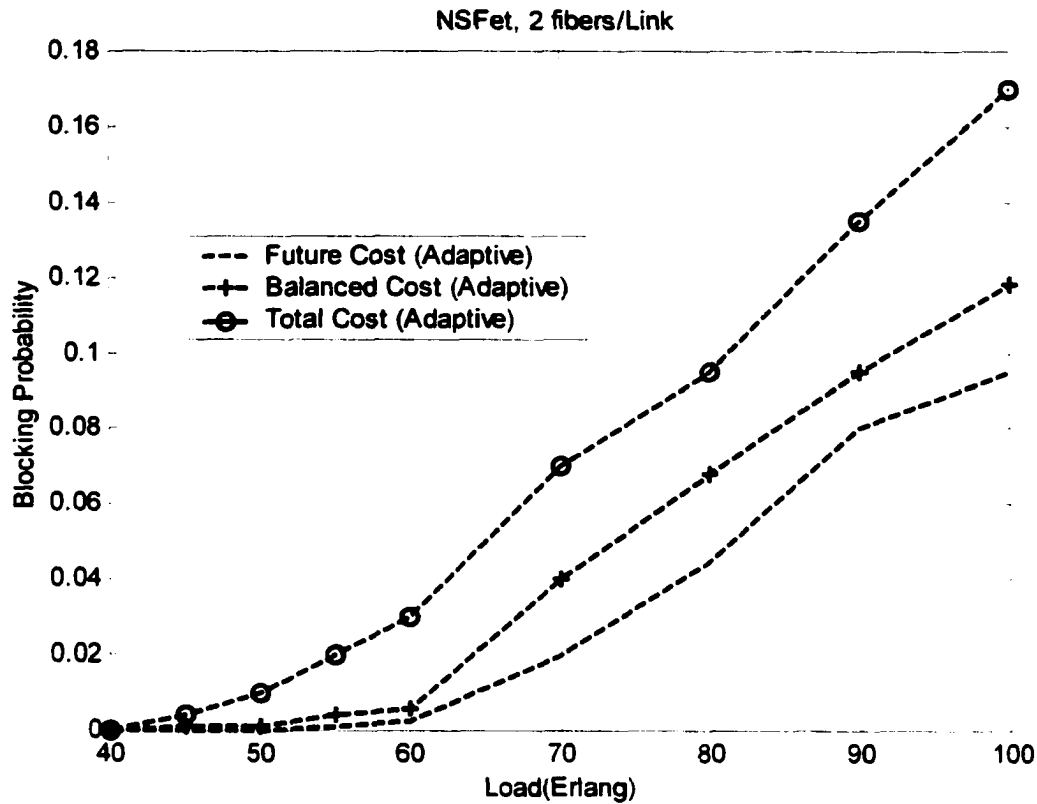


Figure 2.6 Comparison of the different selection schemes for the adaptive routing case

Fig. 2.6 shows the simulated blocking probability vs. the call arrival rate of the full- adaptive algorithm for all the three path selection schemes described above. As can be seen from the Fig., the path selection process based on future cost performs the best, followed by the path selection process based on the balanced cost, then by the path selection process based on total cost. Also included in the figure is the adaptive First Fit (FF) algorithm [14]. Note that the performance of the future cost algorithm is significantly better than that of the FF. However, the performance of the balanced cost is almost the same as that of the FF (same results were also obtained in [14] with the DRCL algorithm), and both of them outperform the total cost scheme.

Fig. 2.7 shows the required number of wavelengths vs. the calls arrival rate for three different cases. i) A system that uses end-to-end dedicated backup paths to provide 100% protection against single link/node failures ii) A system that uses end-to-end shared backup paths to provide 100% protection against single link/node failures (iii) A system that provides no protection at all. As expected, the number of wavelength required to provide shared protection is considerably less than that required for the dedicated case, this also was reported in [26].

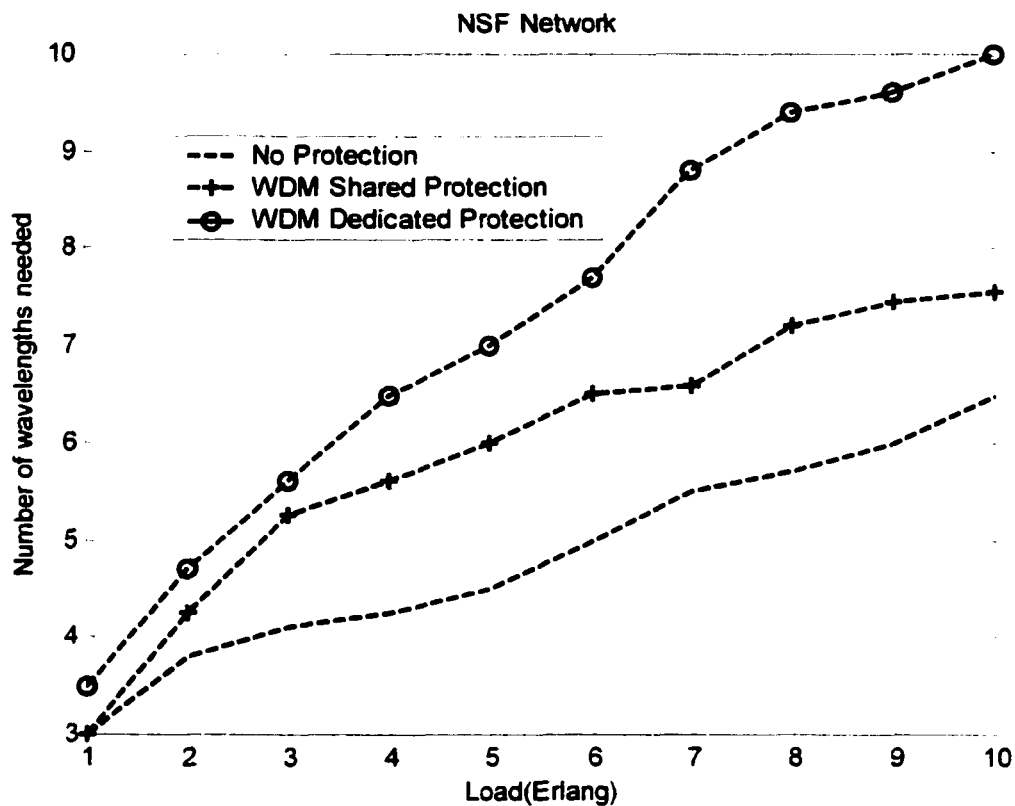


Figure 2.7 Comparison of the dedicated protection vs shared protection

2.6 Real-time provisioning at the optical layer

Provisioning end-to-end circuits is an endless source of struggle for service providers and a frustration for end-users. Provisioning of connections requires algorithms for route selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. In this section, we examine the problem of route selection in the context of applying/adapting the RWA algorithm presented above to each of the three interconnection models described in section 2. The implications on both the route selection and signaling mechanism components will also be outlined for each of the three interconnection models.

2.6.1 Dynamic Lightpath Computation

Dynamic computation of a lighthpath involves the implementation of two traffic engineering components: an information distribution mechanism that provide knowledge of the relevant attributes of available network resources, and a path selection process that uses the information distributed by the dynamic link-state advertisement algorithm to select a path that meets the specific requirements of the traffic flow. In a fully distributed IP-over-optical network implementation, these are:

- 1) **An information distribution mechanism-** that provides knowledge of network's topology and the available resources. This component is implemented by defining relatively simple extensions to the interior gateway protocol (IGP), e. g. open shortest path first (OSPF) so that link attributes are included as part of each router's link-state

advertisement. Some of the traffic-engineering extensions that need to be added to the IGP link-state advertisement include maximum link bandwidth, maximum reservable link bandwidth, current bandwidth reservation, current bandwidth usage, and link coloring [30]. These extensions capture optical link parameters and any constraints specific to optical networks. Such topology and link state information is then flooded to all nodes via updates. Another important component is to define naming and addressing convention for different elements of the physical plant hierarchy [11]. Here, we have defined and assigned a naming and addressing convention for different elements of the physical plant hierarchy, i.e., by implementing a simplified link-state advertisement algorithm to model extended OSPF. This algorithm is capable of periodically updating and advertising all of the above link attributes. The link state updates can be triggered, for instance, based on a given threshold of the number of available wavelengths per fiber, below which the updates can be triggered. Once each node has a representation of the full physical network topology and the available resources on each link, a path selection algorithm is required, i.e., dynamic RWA.

- 2) **A path selection process-** that uses the information distributed by the dynamic link-state advertisement algorithm to select an explicit route that meets the specific requirements of the traffic flow. This process can be performed either off-line or on-line using a constraint-based routing calculation. The source router (peer model), or the border OXC/central management node (augmented/overlay models) are basically responsible for computing the complete path all the way to the destination through the optical domain, and then initiating path setup using the signaling protocol (e. g., CR-

LDP or RSVP). The route may be specified either as a series of nodes (routers/OXCs), or in terms of the specific links used (as long as IP addresses are associated with these links).

2.6.2 Route Selection Using the Proposed RWA

Numerous policies can be used to route lightpaths through the network, such as the constraint-based routing algorithms proposed here. This scheme can be used directly for computing the route and assigning the wavelength for both the overlay and the augmented models. In this case, a connection request is initiated by a client IP/MPLS router (border router, that is a router directly connected to the optical network) and sent to an ingress optical node (border OXC, that is the OXC connected to the border router) using UNI signaling. Such provisioning request may specify the desired destination client router. Note that the source end-point is implicit in this case. The ingress optical node processes the request, and computes an appropriate route along with a wavelength through the network (using topology and state information that has been propagated using OSPF link state advertisements). Note that the request may also be received by an ingress OXC from a central management node, specifying the source and destination end-points.

The routing within the optical and IP domains in the case of the augmented model may be separated, with a standard routing protocol running between domains [7-8]. This is similar to the IP interdomain routing model, where the central issue is how the routing information is exchanged at the IP-optical UNI. There are two possibilities for this. The

first is to consider the interdomain IP routing protocol, BGP, which may be adopted for exchanging routing information between IP and optical domains. The second is to consider the use OSPF areas (OSPF supports a two-level hierarchical routing scheme through the use of OSPF areas) to exchange routing information across the two domains [7-8].

However, in the case of the peer model, additional extensions need to be added to the routing protocol (OSPF) so that the segment of the entire route that crosses the optical core (between the ingress and egress OXCs) must be treated as a virtual link of fixed capacity and advertised as such in further OSPF updates. The routing in this case is referred to as a “flat” routing organization [7-8]. Under this approach there is only one instance of the routing protocol running in the IP and Optical domains. An IGP like OSPF or IS-IS with suitable optical extensions is used to exchange topology information. These optical extensions will capture the unique optical link parameters. The OXCs and the routers maintain the same link state database. The routers can then compute end-to-end paths to other routers across the OXCs. This lightpath is always a tunnel across the optical network between edge routers. Once created such lightpaths are treated as virtual links and are used in traffic engineering and route computation. As and when forwarding adjacencies (FAs) are introduced in the link state corresponding links over the IP Optical interface are removed from the link state advertisements. Finally the details of the optical network are completely replaced by the FAs advertised in the link state [7-8].

2.6.3 RWA Implications on Signaling Mechanisms

Once a lightpath request from a source is received by the ingress node, it computes the complete path all the way to the destination through the optical domain using the proposed RWA algorithm. The output of this calculation is an explicit route consisting of a sequence of hops that provides the shortest path through the network that meets the constraints. This explicit route is then passed to the signaling component that initiates path setup (to reserve resources) using the signaling protocol, e. g., CR-LDP or RSVP-TE [9]. Note that the implications of using the proposed RWA scheme on the signaling is that the conventional overhead associated with the wavelength request (probe message) is no longer needed, since the RWA scheme select both the route and assign the wavelength simultaneously.

2.7 Conclusion

This chapter has considered the problem of real-time provisioning of optical channels in a hybrid IP-centric WDM-based networking model. Provisioning implies that an optical channel is successfully routed if both an active path (working) and another alternate link-disjoint path (backup) are set up at the same time. Specifically, the work presented here has addressed the implementation issues of the path selection component of the traffic-engineering problem in such a network. Methodologies and associated algorithms for dynamic lightpath computation were outlined.

We have presented and compared the performance of two different constraint-based routing and wavelength assignment (RWA) algorithms, for dynamic provisioning of the optical channels. Specifically, the RWA scheme is used to compute end-to-end dedicated and shared backup paths to protect against single link/node failures. Three path selection schemes have also been proposed for each algorithm. Both algorithms are based on a fully distributed implementation. The performance of both algorithms is then compared with that of the conventional static RWA algorithm. It is shown that the dynamic full-adaptive algorithm outperforms the semi-adaptive one, and both of them significantly outperform the conventional static algorithm. It's also shown that the Future Cost-Based Selection scheme outperforms both the total-based and the balanced selection schemes.

Chapter 3

3. Impact of Wavelength Converters on the Performance of Optical Networks

3.1 Introduction

In more recent years, several dramatic technological advances in the telecommunication arena have emerged to set the foundation for the next-generation-networking paradigm. The most important development, of course, is the rise of optical networking, first with wavelength-division multiplexing (WDM) and more recently with optical multiplexers, and optical cross-connects (OXC). The myriad innovations in WDM technology that increase the number of wavelengths, generate more bandwidth, send multi-gigabit signals faster and longer distances, wideband optical amplifiers, and those enabling OXC - with the ability to add, drop, and in effect construct wavelength-switched and wavelength-routed networks, are now beginning to shift the focus more toward optical networking and network-level issues. As such, it presents an attractive opportunity to evolve WDM technology toward an optical networking infrastructure with transport, multiplexing, switching, routing, survivability, provisioning, and performance monitoring, all supported at the optical layer.

A major driver for realizing this evolution is the potential ability of such networks to provide fast automatic setup and tear-down of paths across the optical network, with the capability of supporting diverse client signals on the paths. The main focus, therefore, of

today's optical network planning lies in implementing a dynamically reconfigurable optical transport layer based on fast OXCs coupled with a suitable control and management architecture.

Thus, in the near future an optical transport network (OTN) will be realized capable of supporting a hundred or more lambdas per fiber, with bit rates on the order of 10–40 Gb/s per lambda, and dozens of fibers per conduit. This model of the network comprises an interconnection of a number of OXCs in a general mesh topology. Since each interconnecting fiber may support many wavelengths (e.g., > 100) and there may be many fibers (e.g., 32), the OXCs require the capability to support the cross-connection of many thousands of wavelength channels. This OTN, therefore, will provide wavelength paths (lightpaths) to clients such as IP/LSR routers, SONET/SDH network elements, and ATM switches.

To provision a lightpath in such WDM networks, a connection must be established along a route using a common wavelength on all of the links along the route. This constraint may be removed by the introduction of wavelength converters, which are devices that take the data modulated on an input wavelength and transfer it to a different output wavelength. Wavelength converters thus improve network-blocking performance. However, the introduction of wavelength converters into WDM cross-connects increases the hardware cost and complexity. An OXC with wavelength conversion capability has been viewed as a key functionality to improve the network efficiency. The trade-off is the additional cost added to the OXC. Partial wavelength conversion has been investigated in order to improve the switch performance while minimizing the switch cost.

These OXCs can switch high-speed optical signals (e.g. OC-48, OC-192) from input ports to output ports. The switching fabric may be purely optical or electrical or a combination. These OXCs may be equipped with full wavelength conversion capability, limited wavelength conversion capability, or no wavelength conversion capability at all. If the WDM systems contain transponders or if electronic OXCs are used, then it is implied that a channel associated with a specific wavelength in the WDM input can be converted to an output channel associated with a different wavelength in the WDM output (i.e. wavelength conversion is inherent). However, if the switching fabric is optical and there is no transponder function in the WDM system, then wavelength conversion is only implemented if optical to electronic conversion is performed at the input or output ports, or if optical wavelength converters are introduced to the OXC.

There has been considerable interest in the literature in the performance improvements offered by the introduction of wavelength converters into dynamically reconfigurable WDM networks. However, most of these studies have assumed that the holding time of the wavelength connection is similar to that of telephone calls. These studies have assumed call models with Poisson arrivals and various holding time distribution and, perform steady-state analysis. Inherent with such analysis is that demand for wavelength connections will arrive in a similar manner to telephone calls and that each connection has fairly short holding time. This is not practical in the current optical network applications since most of connections have to relatively stay permanent.

In general, the performance improvements offered by wavelength converters depend on a number of factors, including network topology and size, the number of

wavelengths, the connection holding time, and the routing and wavelength assignment algorithms used. This chapter investigates the benefit of wavelength conversion in DWDM networks with limited number of wavelength converters assuming a novel traffic model that has not used before. Specifically, we assume a traffic model that represents a more practical situation, namely, that of transporting OC-48 (and OC-192 or higher) "private line" traffic. This traffic is characterized by very long holding time (typically in months) and tends not to be rearranged, since connection path rearrangements often cause traffic "hits" (short time failures). We consider novel switch architecture with partial wavelength conversion capability. For the network topology and traffic pattern considered, the simulation results indicate that the performance of an optical network with only 25% of wavelength conversion capability is very close to that of an optical network with full wavelength conversion. In another Metro application, we observe that the use of wavelength converters does not have any impact on the network performance.

The remainder of this chapter is organized as follows. Section 2 presents a review of the impact of wavelength converters on the performance of WDM networks. In Section 3, we present the switch architecture used here. Section 4 presents the network modeled. The performance analysis and simulation results are presented in section 5. Finally, section 6 offers summary and conclusion.

3.2 Background and Overview

In WDM networks, assigning network resources to successfully carry the connection requests (lightpaths) is well known as the routing and wavelength assignment problem (RWA) [1]. The RWA problem has been extensively studied over the past few years and shown to be NP-complete [1]. With this, the conventional approach is to consider the two aspects of routing and wavelength assignment disjointly by first finding a route along which the connection can be established and then search for an appropriate wavelength to be assigned on all links along the selected route. A number of different routing and wavelength assignment approaches have been investigated in the literature; solutions range from static routing to adaptive routing and for different types of traffic (static, incremental and dynamic). With static traffic, the entire set of connections is known in advance, and the problem is then to set up lightpaths in a global fashion while minimizing network resources such as the number of wavelengths or the number of fibers in the network. Here, the RWA problem for static traffic is known as Static Lightpath Establishment (SLE) and can be formulated as mixed-integer linear program [2]. In the incremental-traffic case, connection requests arrive sequentially, a lightpath is established for each connection, and the lightpath remains in the network indefinitely. For the case of dynamic traffic, a lightpath is setup for each connection request as it arrives, and the lightpath is released after some finite amount of time. The objective in the incremental and dynamic traffic cases is to setup lightpaths and assign wavelengths in a manner that minimizes the amount of connection blocking [2]. This problem is referred to as the Dynamic Lightpath Establishment (DLE). Generally, the DLE is more difficult to solve,

and therefore, heuristics methods are generally employed. Heuristics exist for both the routing sub-problem and the wavelength assignment sub-problem.

For the routing sub-problem, there are three basic approaches that can be found in the literature: fixed routing, fixed-alternate routing, and adaptive routing [2]. Fixed routing is one variant of the “static routing” in which routing decisions do not vary with time. Moreover, in fixed routing the same fixed route for a given source-destination pair is always selected. The fixed alternate routing approach considers multiple routes between a source-destination pair and each node in the network maintains an ordered list of a number of fixed routes to each destination node. When a connection request arrives, the source node attempts to establish the connection on each of the routes from the list in sequence, until a route with a valid wavelength assignment is found. Conversely, in adaptive routing [2,3,4,5], the route from a source node to a destination node is chosen dynamically, depending on the network state. Adaptive routing requires extensive support from the control and management protocols to continuously update the routing table at the node. An advantage of adaptive routing is that it results in lower connection blocking than fixed and fixed-alternate routing.

Meanwhile, for the wavelength assignment sub-problem, a number of heuristics have been proposed [2]. These heuristics are Random Wavelength Assignment, First-Fit, Least-Used, Most-Used, Min-Product, Least-Loaded, MAX-SUM, Relative Capacity Loss, Wavelength Reservation, and Protecting Threshold. For a tutorial review on the RWA problem, we refer the reader to [2]. Note that, one requirement in all optical networks is that a lightpath between two nodes along a particular route must use a single

wavelength on all links along the path. This requirement is referred to as the wavelength continuity constraint and can be avoided by the introduction of wavelength conversion (also referred to as wavelength translation or wavelength changing). In general, a wavelength converter is a device, which takes at its input a data channel modulated onto an optical carrier with a wavelength λ_{in} , and produces at its output the same data channel modulated onto an optical carrier with a different wavelength λ_{out} . If wavelength converters are included in the OXCs in WDM networks, connections can be established without the need to find an unoccupied wavelength, which is the same on all the links making the route. This means that networks with wavelength converters are equivalent to traditional circuit switched networks. Wavelength converters thus result in improvements in network performance.

Analysis of the performance improvement with wavelength converters is very important for the design of optical networks. There are many studies on the impact of wavelength converters in DWDM networks. In [6,7], a very comprehensive review of the wavelength conversion from technology, application and benefits points of view are given. In general, the wavelength conversion gain depends on many factors such as topology (in particular network size and connectivity), number of wavelengths per fiber, traffic load, and routing and wavelength assignment algorithms. Fully connected networks constitute an extreme case of connectivity where there is no gain in using shortest path routing algorithms. At the other extreme is the ring topology for which the gain of wavelength conversion is relatively small. It has been shown that mesh networks can achieve the largest gain with wavelength conversion [8].

In [9,10,11], the authors have studied the effect of network topology and number of wavelengths on the wavelength conversion gain for single fiber networks using shortest path routing and random wavelength selection algorithms. Several heuristic algorithms for route selection and wavelength assignment have been studied [12] in single fiber optical networks. In [13], the authors have showed that the benefit of wavelength conversion rapidly disappears as the number of fibers per link increase.

Significant performance improvements are often obtained in circuit-switched networks, and equivalently in networks with wavelength converters, if alternate routing is introduced. The authors in [14, 15, 4, 16, 3] have investigated the performance of wavelength continuous single fiber networks with alternate routing. They have considered various routing and wavelength assignment schemes, and have shown that the performance of wavelength-continuous networks is strongly dependent on the schemes used. In [15], a routing scheme which chooses a route from among the k shortest routes which maximizes the ratio of the route length (H) to the interference length (L), (H/L), was proposed. As the number of possible alternate routes, k , increases, H/L increases and the wavelength continuous blocking probability was shown to increase with increasing k in the network topology considered in [15]. In contrast the blocking probability with wavelength converters decreases by increasing k , due to the increased set of possible routes through the network for establishing a light path. Thus the performance improvements offered by wavelength converters increases.

3.3 Switch Architecture

We consider an OXC switch architecture with flexible wavelength conversion capability as shown in figure 3.1. It consists of multiple wavelength space switch fabrics, and a flexible wavelength conversion module. Each wavelength space switch has $N+M$ input and output ports of which, M input/out ports are connected to the wavelength conversion module. Assuming that the number of wavelengths per fiber is W , the size of the wavelength conversion module will be $W*M$. For example, a 4×4 fiber switch with 4 wavelength per fiber and $M=1$ wavelength conversion module access capability will allow 4 wavelength conversion simultaneously. That is, any four wavelengths from different wavelength group can be converted to other wavelengths at the same time. If we increase the number of M to 2, the number of wavelengths that can be converted will be increased to 8.

Since we have assumed that the wavelength converters are attached to each wavelength space-switch, the wavelength converter module is not shared by all the wavelengths in the sense that only M wavelength count in each wavelength color can access the wavelength converters simultaneously. It is expected that the performance of the non-shared case should be worse than the shared case.

Obviously, the larger the value of M ($M \leq N$), the more flexibility there is in choosing wavelength connection paths, and the better the OXC performance will be due to less blocking probability. On the other hand, the larger the value of M , the more

complex the OXC is (therefore, more costly). One question that immediately rises is the optimal value for M . In other word, it is worth to study how much wavelength conversion one should add to the switch fabric in order to achieve similar performance as a switch with full wavelength conversion capability.

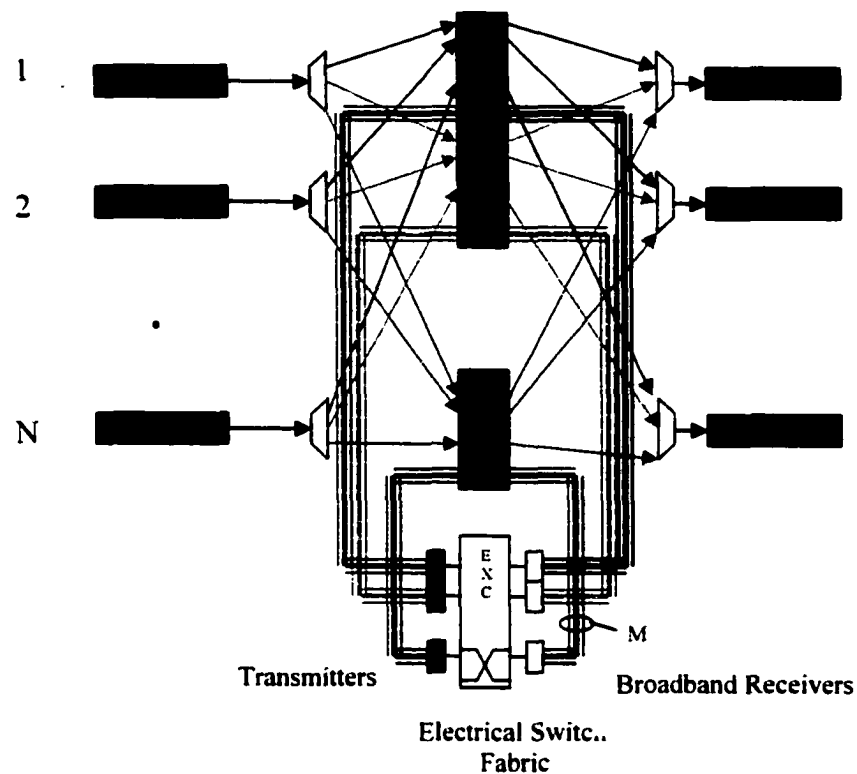


Figure 3.1. OXC switch architecture with limited number of wavelength converters.

3.4 Network Model and Assumptions

In this section we state the assumptions about the network and traffic that are used in our simulation for calculating the path blocking probability of an optical network with and without wavelength conversion. We consider the 21-node ARPA-2 network (Fig. 3.2) with 26 duplex links, along with another smaller network (NSFNET) where each link has the same number of wavelengths (W).

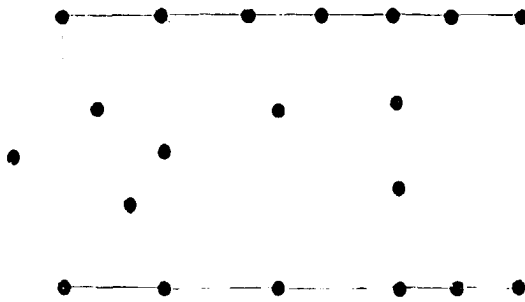


Fig 3.2.a The ARPA-2 Network

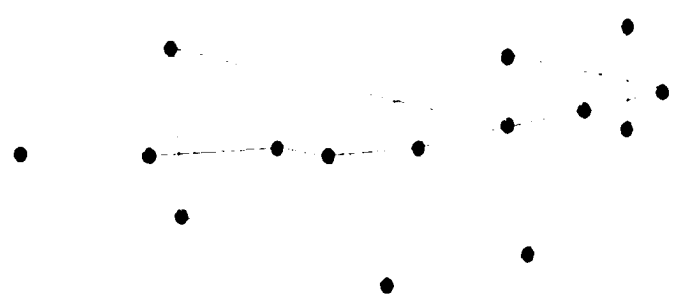


Fig. 3.2.b NSFNET

Fig 3.2 Network topologies.

We choose a traffic model that has not generally been considered in the literature. The most common models existing in the literature have extended circuit-switched call models to the DWDM networks. One generally uses call models with Poisson arrivals and various holding time distributions and, performs steady-state analysis. Inherent with such analysis is that the demand for wavelength connections will arrive in a similar manner to telephone calls and that each connection has fairly short holding time. However, at present we do not believe that such a model represents realistic scenarios for optical networks. In this chapter we assume a traffic model that represents a more

practical situation, namely, that of transporting OC-48 (and eventually OC-192 or higher) “private line” traffic. This traffic is characterized by very long holding times (average in months) and tends not to be rearranged, since connection path rearrangements often cause traffic “hits” (small failures) to the connections which, to very high speed traffic, results in significant data disruption. This traffic model implies that the network will eventually reaches a “saturation state”, rather than a steady state.

3.5 Performance Evaluation

The blocking probabilities experienced in a wavelength-continuous WDM network depend on the routing and wavelength assignment schemes used. In wavelength-routed optical networks, the RWA problem consists of two components. The first is to determine a path (the set of links) along which the connection can be established. The second problem is to assign a wavelength (or a set of wavelengths) to the selected path. In a network without wavelength converters an end-to-end light path must use the same wavelength on all links along the selected path. With this constraint, the set of wavelengths could be searched in a fixed order or an adaptive order. Conversely, in a network with wavelength converters, a combination of different wavelengths could be assigned to a single end-to-end light path.

Generally speaking, the richer the set of routes, the more likely it is that a good solution will be found. Hence, and to add more options to the routing decision, a number of alternate paths are computed. We develop a routing algorithm based on the classical Dijkstra shortest path; shortest paths are computed based on a minimum number of hops

basis. In fixed alternate routing each s-d pair is assigned a set of paths, and this set may be searched in a fixed or adaptive order to find an available path. Fixed alternate routing is a constraint path selection in which a path is selected from a predetermined set of candidate paths. For example, these candidate paths may include the shortest-path route, the second-shortest-path route, the third-shortest-path route, etc.

While fixed alternate routing provides simplicity of control for setting up and tearing down light paths, it may also be used to provide some degree of fault tolerance upon link failures. Another advantage of fixed-alternate routing is that it can significantly reduce the connection blocking probability compared to fixed routing (where one always chooses the same fixed path for a given s-d pair). We propose two different alternate routing algorithms, the k link-disjoint paths and the k best paths [20]. To successfully setup a lightpath for the call in demand, a wavelength is searched and assigned along the links on the selected path. If none of the shortest paths between s and d is found such that a single wavelength can be assigned, then instead of blocking the call, we proceed by searching for a possible combination of wavelengths that can be assigned along the path. Many wavelength assignment schemes can be considered when wavelength conversion is needed, out of which we only addressed the following:

First Fit (FF): we search the links in the state matrix (a matrix describing the state of the network at any time t) that are associated with the path starting from wavelength number 0, and the first wavelength which is available on each link or links along the chosen path. Note, this will result in a sequence of wavelengths to be assigned to the path since we assumed that a single wavelength is not available on the path.

Minimum Converters Used (MCU): In this scheme we try to find a combination of wavelengths that use the fewest number of converters along the path by doing an exhaustive search for the optimum wavelength assignment.

Note that, call rejection may be due to the following constraints: 1) bandwidth constraint: no sequence of channels lies on any of the k-paths between the origin and the destination of the requested call; and 2) converter constraint: no wavelength converters are available at the intermediate nodes where wavelength conversion of the connection is needed if the bandwidth constraint is satisfied.

A simulation method is used for examining the impact of limited wavelength converters on the network models and traffic assumptions proposed in the previous section. Results have shown that similar performance (total number of accepted calls) is obtained when comparing both proposed wavelength assignment schemes, however the overhead added when using the MCU assignment scheme is the computation time since an exhaustive search is required to find the set of wavelengths that minimizes the number of converters used along the path. Hence, in the following discussions, all results are obtained by using the FF assignment scheme.

First, we show the performance improvement in the ARPA-2 network with 8 wavelengths per fiber for a given amount of traffic. Results show that 25% (Fig. 3.3) wavelength conversion is needed to achieve almost similar performance as networks with full wavelength conversion, and a modest improvement (almost 7.35% improvement) to network without wavelength conversion.

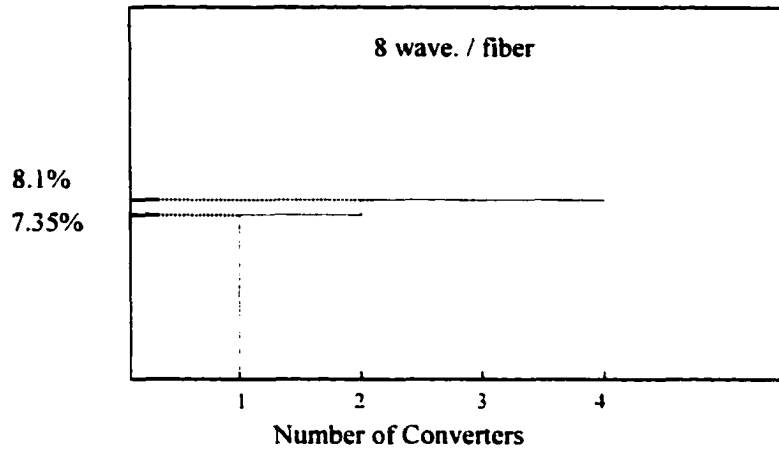


Fig 3.3 Performance Improvement

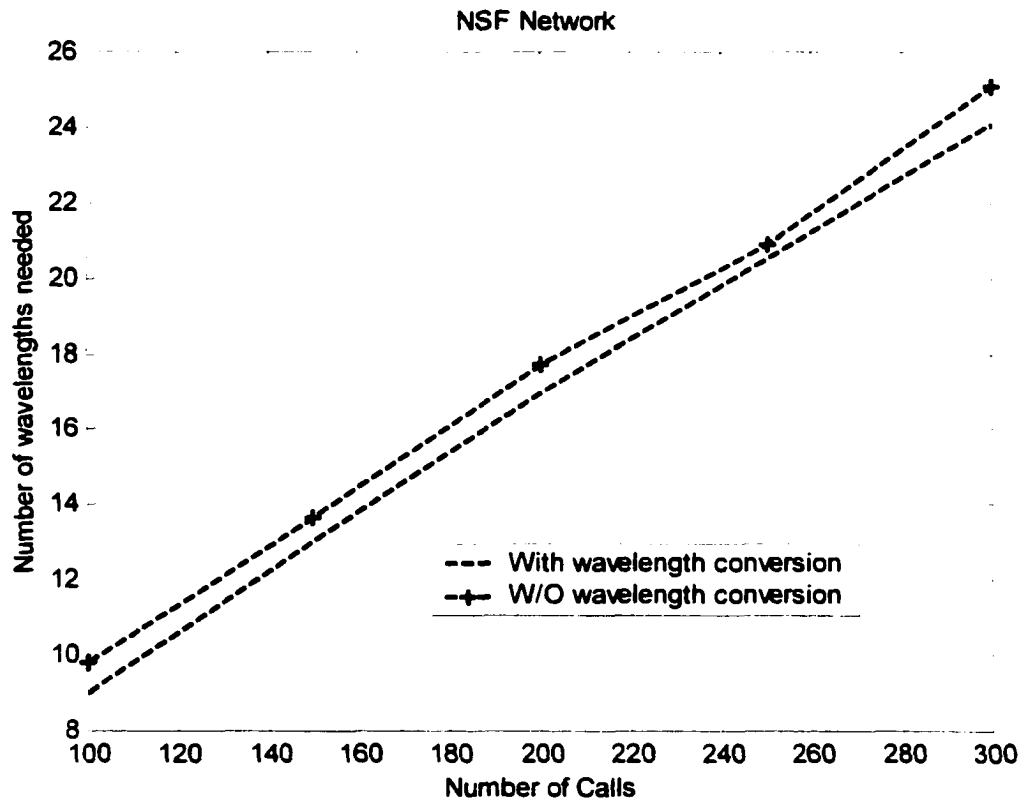


Fig. 3.4 Comparison of performance improvement between networks with and w/o wavelength conversion

In Figure 3.4, we plot the number of wavelengths needed to accommodate a given number of light paths for the NSFNET, without and with full wavelength conversion. The improvement with wavelength conversion is minimum. Clearly it can be seen that wavelength conversion yields little improvement (Fig. 3.4), and almost the same number of wavelengths is needed in both cases to satisfy the zero blocking probability imposed.

To study further the impact of wavelength conversion, we show how the route length can dramatically affect the performance of the network. In general, blocking in a wavelength continuous network increases with increasing route length, as it becomes increasingly difficult to locate a common wavelength on each hop of a route. This effect is considerably less dramatic in networks with wavelength converters, because a connection can access any wavelength on each link along the route.

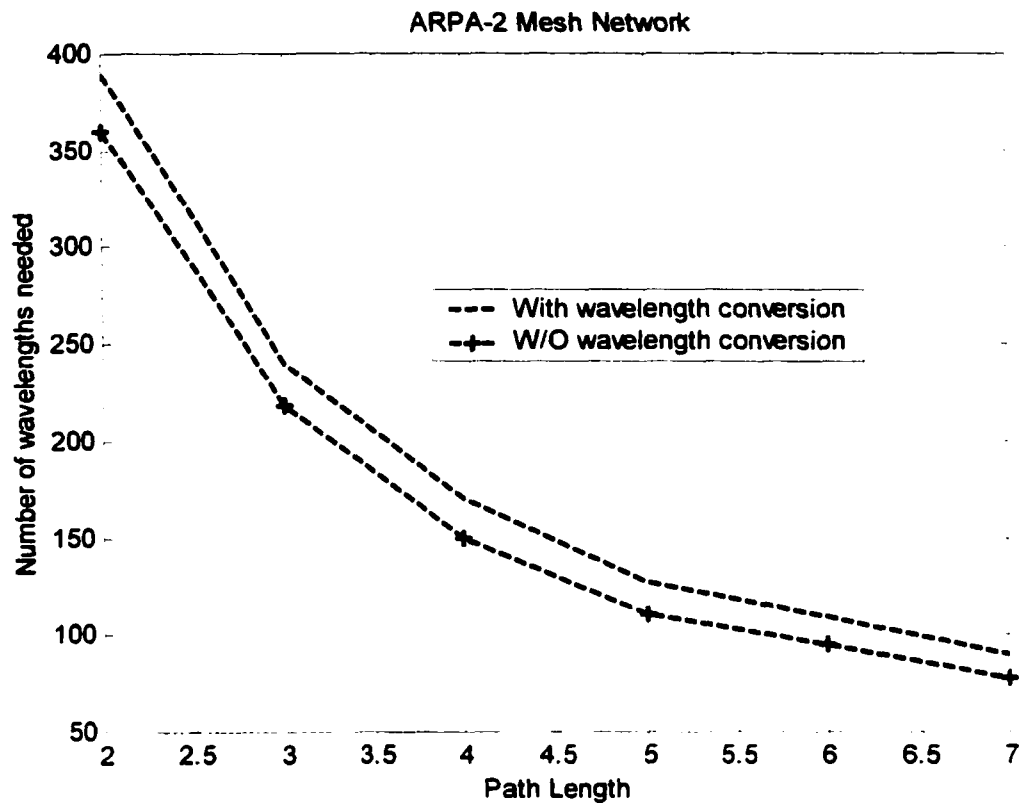


Fig. 3.5- Number of accepted calls versus path length

To show this, we try to route 3000 calls along the ARPA-2, with 8 wavelengths per fiber. Figure 3.5 shows the number of calls accepted versus the route length; we observe that by increasing the route length, the benefit of wavelength conversion increases since longer paths create more wavelength conflicts for networks with wavelength continuity constraints. In figure 3.5, the improvement due to wavelength conversion increases from 8% in the case where the route length is 2 up to 15% in the case where the route length is 7.

Next we compare the proposed fixed alternate routing schemes. A total of 200 calls are generated and routed along the ARPA-2 network, with 8 wavelengths per fiber.

Figure 3.6 shows the number of calls accepted versus number of converters per OXC; we observe that with the k best routes (k is set to 3 but we stored all the possible routes between two nodes), the throughput is improved by 2%, while we get the same improvement when wavelength conversion is employed.

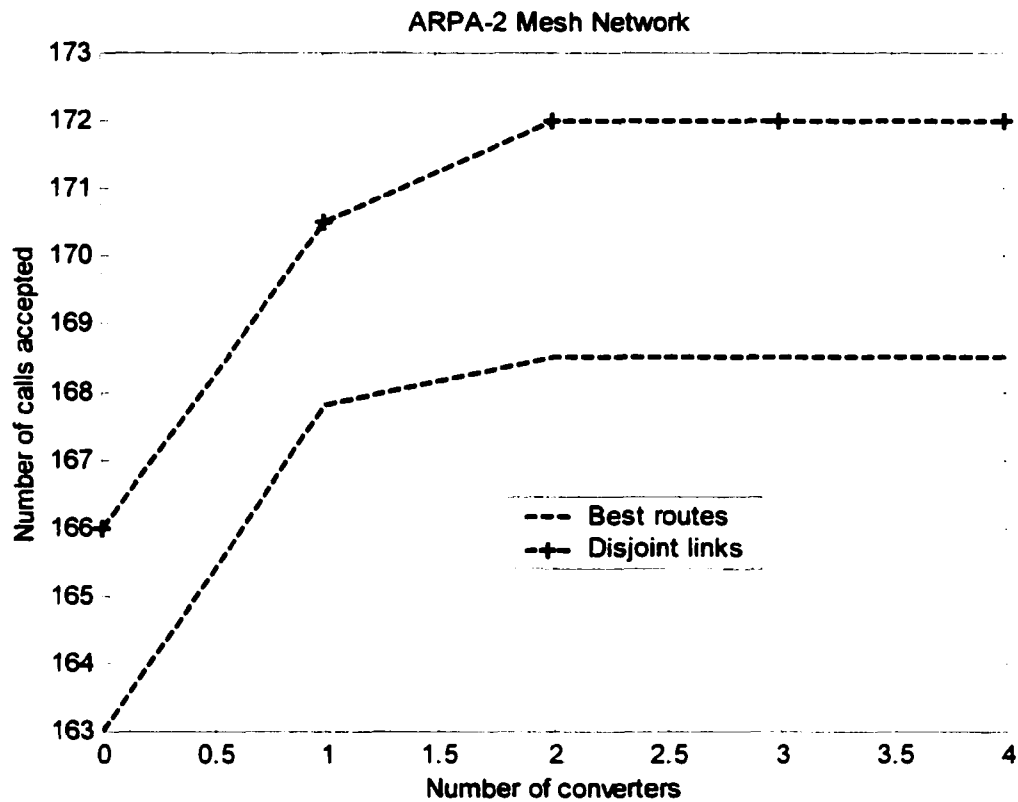


Fig. 3.6 Comparison between disjoint links and k best routes.

While infinite holding time for connections reflects a more realistic assumption in an optical network, such assumption has a drawback on the network performance in general and on the gain of wavelength conversion as well. To see the impact of this, we change the assumptions about traffic that are used in our simulation for calculating the path blocking probability. We assume that connection requests arrive to a node according to a Poisson process with rate λ with uniformly selected destinations and exponentially

distributed holding time with mean $1/\mu$. The performance metric used in here is the blocking probability gain. That is the ratio of the blocking probabilities with and without wavelength conversion. First, it's clear that as the network load increases, the benefit of wavelength conversion decreases. In figure 3.7 we plotted the gain in wavelength conversion versus the traffic load for different holding times. At low traffic load, the increase in the holding time affects dramatically the gain in wavelength conversion. For example at arrival rate equals 1 call per unit time, a gain of 4 is achieved when the holding time is 20-unit time comparing to 1.4 when an 80-unit time holding time is used. Obviously, if we increase more the holding time, the gain will drop to one and almost no gain is offered by wavelength conversion. On the other as the arrival rate increases, the gain gets closer to unity and again the gain offered by wavelength conversion is relatively very small.

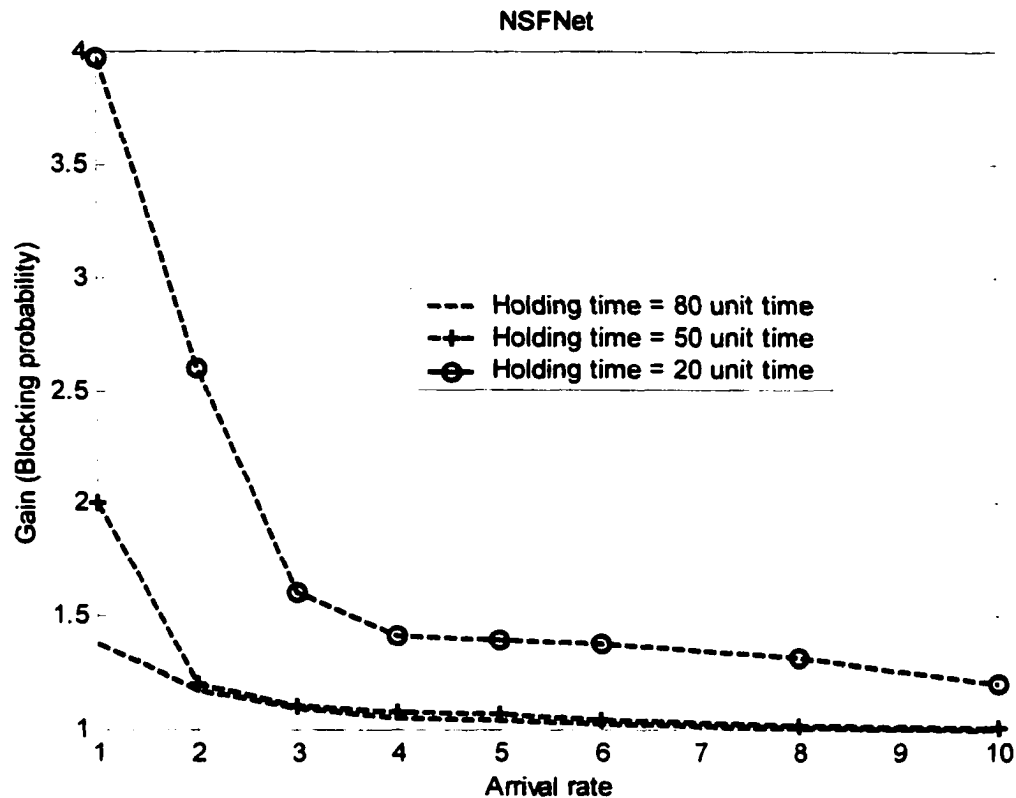


Figure 3.7 Gain vs. Traffic Load

3.6 A Special Case in Metro Application

In this section, we consider a metro ring application with hub traffic pattern as shown in Figure 3.8. This ring architecture is typically used, for example, as an ISP POP access to high bandwidth long haul Internet. One node in the ring is dedicated as a hub node, which serves as a gateway to the long haul network and other nodes on the ring are local nodes. All the traffic starts from the local nodes, and goes through the hub node to access the long haul network. In the opposite direction, the traffic goes to the local nodes on the ring from the long haul network through the hub node.

In this case, all local nodes require a clear channel or one dedicated wavelength to the hub node. In the uplink direction (from local nodes to hub node), all the traffic from local nodes will be terminated at the hub node. The hub node will perform traffic grooming, and 3R functions before the traffic is forwarded to the long haul network. Assuming that each local node requires one dedicated wavelength connection to the hub node, and all the connections follow the shortest path in the ring when the wavelengths are assigned, the most demanding links in terms of the number of wavelengths required are the links between the hub node and its two neighboring nodes. If there are N nodes in the ring (including the hub node), the number of wavelengths needed is equal to $N/2$. It is obvious that wavelength conversion do not help to save the use of wavelengths at all in this case.

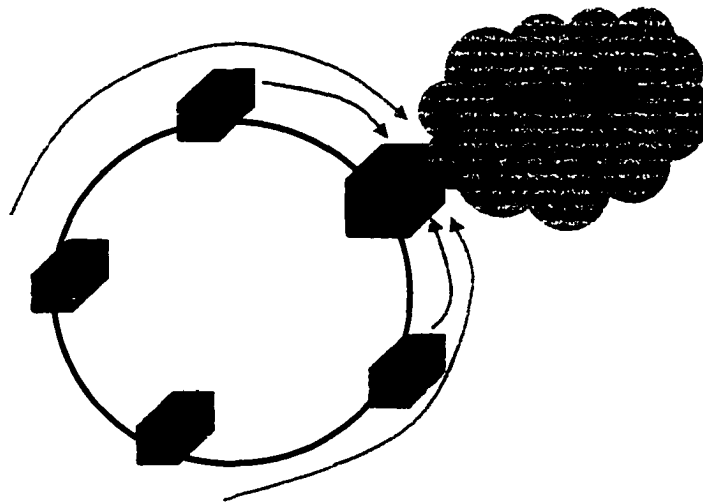


Figure 3.8- Metro Ring Application

In Figure 3.9, we present our simulation results for a ring topology with 8 nodes. end to end connections are generated uniformly at each node and with equal probability,

the calls are destined to the remaining 7 nodes. The number of wavelengths needed to accommodate a given set of connections is plotted versus the number of connections for the cases with and without wavelength conversion. Again we have noticed that the improvement using wavelength conversion is very small.

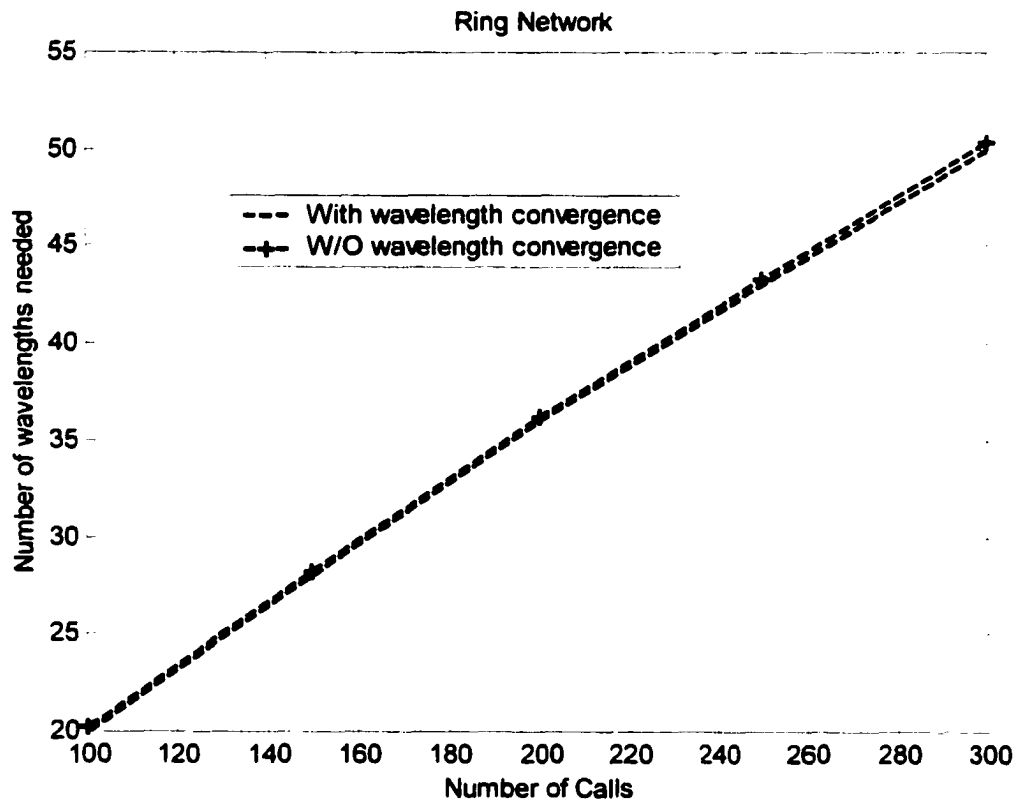


Figure 3.9 Impact of wavelength conversion on an 8-nodes ring topology

3.7 Conclusion

This work presents a quantitative analysis on the benefit of wavelength conversion in DWDM networks with limited number of wavelength converters assuming a novel traffic model that has not used before. Specifically, we have assumed a traffic

model that represents a more practical situation, namely, that of transporting OC-48 (and OC-192 or higher) “private line” traffic. This traffic is characterized by very long holding time (typically in months) and tends not to be rearranged, since connection path rearrangements often cause traffic “hits” (short time failures). Novel switch architecture with partial wavelength conversion capability has also been considered. For the network topology and traffic pattern considered, the simulation results have indicated that the performance of an optical network with only 25% of wavelength conversion capability is very close to that of an optical network with full wavelength conversion. In another Metro application, we observe that the use of wavelength converters does not have any impact on the network performance.

Chapter 4

Connection Management Protocols for WDM Optical Networks

4.1 Introduction

The Internet transport infrastructure is moving towards a model of high-performance IP/GMPLS routers interconnected by intelligent optical core networks that will directly provide a global transport infrastructure for legacy and new IP services. A major driver for realizing this evolution is the potential ability of such techniques to setup lightpaths across the optical network. Current research focuses on the use of distributed management schemes such as General multi-protocol label switching (GMPLS) 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 (MP λ S) is more commonly used [1-4,6]. The IETF has already addressed the interworking of routers and optical switches through the MP λ S initiative. The main goal of this initiative is to provide a framework for real-time provisioning of optical channels, through combining recent advances in MPLS traffic-engineering control plane with emerging optical switching technology in a hybrid IP-centric optical network. Several

interconnection models between the IP and the optical networks have been proposed by the above-cited IETF drafts including overlay, augmented, and peer-to-peer models.

Provisioning of connections requires algorithms for route selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. The implementation of wavelength-routed networks requires the implementation of control and management protocols to perform routing and wavelength assignment functions, as well as to exchange signaling information and to reserve resources. The problem of route selection in such wavelength-routed networks is referred to as the “routing and wavelength assignment (RWA)” problem [1]. When a connection request arrives to the network, the basic problem is to find a route and assign a wavelength to the connection. Several different routing and wavelength assignment approaches have been investigated in the literature [5,8]. The routing algorithm is generally categorized as being either fixed or adaptive. An example of a fixed algorithm is fixed *shortest-path routing (FSPR)* algorithm [5,8], in which a connection always chooses the same fixed shortest route for a given source-destination pair. While fixed algorithms are fairly simple to implement and require very little, if any, state information, they have a higher blocking rate of connection requests.

In an adaptive algorithm, the route will typically depend on the state of the network. One adaptive routing approach is fixed *alternate shortest-path routing (ASPR)* algorithm in which each node in the network is required to maintain a routing table that contains an ordered list of a number of fixed routes to each destination node. When a

connection request arrives, the source node attempts to establish the connection on each of the routes maintained in the routing table in sequence, until a route with a valid wavelength assignment is found. Another approach to adaptive routing is *fully adaptive routing*, which is presented in [10]. Each node maintains the complete network topology, including the information about wavelengths that are in use in each link. Based on this global information, the node can calculate an optimal route to a destination on a given wavelength. The node can then reserve the desired wavelength on each link in the route in order to setup a connection. One drawback of such an approach is that whenever a connection is established or taken down, the state of the network changes, and all nodes must be informed of the new state. This requirement can lead to high control message overhead and possibly slow network routing convergence. Thus, while *fully adaptive routing* approach may be appropriate for a semi-static network in which connections are not changing rapidly, it may not be appropriate for emerging networks in which connections and lightpaths are established and taken down more dynamically [5.8].

In addition to routing schemes, signaling protocols are needed to establish connectivity within the network along the chosen route. Two types of signaling protocols have been investigated in the literature, namely forward and backward signaling protocols [9]. In the forward protocol, the source starts reserving all wavelengths. at each link along the entire path, which are available on all the links traversed in the forward direction. When the reservation message reaches the destination node, the destination then chooses one wavelength from the wavelengths reserved along the entire path and releases the remaining wavelengths. The drawback of this forward reservation scheme is

that network resources are being over reserved while the connection request proceeds toward the destination. This may lead to the blocking of subsequent connection requests and, hence, lower network utilization. In the backward scheme, the source node sends a setup control message to the destination without reserving any resources. This setup control message will collect information about wavelength usage along the path. Upon receiving the setup control message, the destination node starts reserving wavelengths along the path towards the source node. In this chapter, the backward reservation protocol is used.

There are two options for MPLS-based signaling protocols, Resource ReSerVation Protocol Traffic Engineering Extensions (RSVP-TE) or Constraint Based Routing Label Distribution Protocol (CR-LDP). There are some basic differences between the two protocols, but both essentially allow hop-by-hop signaling from a source to a destination node and in the reverse direction. Not all features present in these protocols are necessary to support lightpath provisioning. In addition, the implementations of these protocols require global state information exchange among all network nodes. On the other hand, certain new features must be introduced in these protocols for lightpath provisioning, including support for bi-directional paths, support for switches without wavelength conversion, support for establishing shared backup paths, and fault tolerance.

This chapter proposes two new distributed signaling protocols for fast automatic setup and tear-down of paths across the emerging interconnection models for IP-over-

optical- networks. Specifically, the first scheme is flooding-based routing (FBR) algorithm with backward reservation while the second scheme is based on an adaptive routing algorithm called *Multi-Path Routing (MPR)* where k paths are probed simultaneously. Two path selection schemes are considered for the MPR approach, namely first come first serve (FCFS) path selection scheme and least-congested path (LCP) selection scheme. Our objective in developing these protocols is twofold: first, to avoid the implementation complexities associated with MPLS-based CR-LDP and RSVP-TE signaling protocols; and second, to adapt the performance optimization algorithm to the requirements of different user applications by having the flexibility to vary the relative weight assigned to each of three performance metrics [call acceptance rate (CAR), call set-up time (CST), and routing distance (RD)].

The main characteristic of the proposed schemes are: 1) the destination node makes both routing and wavelength selection decisions adaptively; 2) no global state information exchange among network nodes is needed for either scheme; 3) both schemes attempt to combine the benefits of both the conventional preferred neighbor (poor CST) and forward-based flooding (poor CAR) approaches [11] in a way to improve all the three performance metrics simultaneously; 4) both schemes are able to achieve a lower ACST and ARD compared to that of CR-LDP, RSVP-TE and the preferred neighbor due to their non-backtracking nature, since all k paths are probed simultaneously; and 5) both schemes use backward-based reservation signaling to alleviate the excessive reservation of resources. These features lead to higher CAR.

Also this chapter investigates and compares the performance of the global information-based link state approach and a local-information based fixed alternate link routing approach. The global information-based link state approach consists of both an integrated RWA algorithm and a signaling algorithm. Two triggering mechanisms for the LSAs update procedures are considered; one is periodically-based and the other is threshold-based update. The local-information based fixed alternate link routing approach where the signaling protocol is closely integrated with the RWA protocols. No update messages are required in this approach.

Discrete-time simulation tool is developed to examine the effectiveness of the proposed algorithms in terms of all the three performance metrics as well as the bandwidth required for control messages. The remainder of this chapter is organized as follows. In Section 2.2, we present the network model. Section III describes the proposed signaling algorithms and control mechanisms. Numerical results from simulation are presented in Section IV, and Section V concludes the chapter.

4.2 An overview of Distributed Wavelength Reservation Protocols

A distributed reservation protocol, under the condition of rapidly changing availability of resources in a WDM network, should correctly and efficiently reserve necessary and available wavelengths during lightpath (i.e., connection) set-up time [14,15] and again release those resources when they are no longer needed. This

reservation is normally accomplished with the help of a few control packets [9,10] exchanged between the source-destination pair prior to the start of data transfer. There are two classes of distributed reservation protocols [8,9], namely forward reservation protocols (FRPs), and backward reservation protocols (BRPs). Forward (backward) reservation protocol is also known as source- (destination-) initiated protocol because the source (destination) node begins the actual reservation process. In both types of reservation protocols, the source node sends out the first control packets towards the destination node either to reserve (in case of FRP) or to probe (in case of BRP) the available wavelengths enroute. The destination node selects one of the reserved (FRP) or potential (BRP) wavelengths and issues the second control packet back to the source node to release the unselected wavelengths (FRP) or to reserve the selected wavelength (BRP). These protocols are briefly explained below.

4.2.1 Forward Reservation Protocols (FRPs)

In this technique, the source node sends a reservation (RESV) packet to the destination node along the decided route, once a connection request has arrived. Each node along the path process the RESV packet and temporarily locks one or more appropriate wavelengths on the next link for the connection. If no suitable wavelength is found on the next link at the intermediate node, then the node sends a failure (FAIL) packet back to the source. FAIL packet unlocks all the wavelengths reserved thus far on the previous link(s). otherwise, at the destination, one of the wavelengths available in the RESV packet in this regard is picked up, and confirmation (CONF) packet in this regard

is sent back from destination to source. On its way back to the source, the CONF packet permanently locks the selected wavelength and unlocks the other wavelengths at the intermediate nodes. There are many variations of FRP which are discussed below:

Exhaustive: in this case, all available wavelengths in all hops in the selected path are blindly reserved. This protocol is no doubt good for the particular call for which lightpath is being set up, but is equally bad for other contemporary calls which find the resources unnecessarily blocked. Several refinements can be suggested to overcome this drawback resulting into the modified protocols described next.

Selective all: in this case, all the available wavelengths in any hop are not blindly reserved reserved like the exhaustive protocol. Only those wavelengths are reserved, which are already reserved in the previous hop, because a wavelength unavailable in any intermediate hop is surely going to be rejected at the destination.

Selective-N: this is a minor variation of the selective protocol. Here also, a wavelength at any hop will be reserved, if it is also reserved in the previous hop. But there is an upper limit (say, N) on the number of wavelengths that can reserved at any hop. In this technique, the probability of finding a lightpath for the call under consideration decreases, but, at the same time, the probability of finding a lightpath for its contemporary calls increases. So the overall efficiency increases. It can be noted that, when N is equal to the number of wavelengths/fiber, this protocol becomes selective all.

4.2.2. Backward Reservation Protocols (BRPs)

To overcome the main disadvantage of temporarily locking wavelengths (not used finally) in forward reservation, an optimistic approach called backward reservation is proposed [5]. In backward reservation protocols (BRPs), a source node sends a probe (PROB) packet to the destination instead of RESV packet. This PROB packet only gathers the wavelength usage information along the path and does not lock any wavelength. Upon receiving the PROB packet, the destination node decides upon the wavelength to reserve and sends back a RESV packet, which now locks the wavelength (if it is still available) along the reverse path towards the source node. If the node is not found available at some intermediate node, the node generates a FAIL packet to the destination and NACK packet to the source. The FAIL packet releases the wavelength locked so far and NACK packet informs the source about the connection failure.

The main drawback of BRPs is that two contemporary connections, sharing one or more common links, can accidentally select the same wavelength, because both of them have found the wavelength available by their respective first control packets. So one of them will be blocked, though other wavelength(s) may be available for the connection. Hence, there will be an unnecessary blocking which is not legally tolerable. In this chapter, the backward reservation protocol is used.

4.3 An Overview of Global and Local Information based Routing and wavelength Assignment.

When lightpaths are established and taken down dynamically, routing and wavelength assignment decisions must be made as connection requests arrive at the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. The connection may also be blocked if there is no common wavelength available on all of the links along the chosen route. Thus, the objective in the dynamic situation is to choose a route and a wavelength that maximize the probability of setting up a given connection, while at the same time attempt to minimize blocking for future connections. Similar to the case of static lightpaths, the dynamic RWA problem can be also decomposed into a routing sub-problem and a corresponding wavelength assignment sub-problem.

Approaches to be solving the routing sub-problem can be categorized as either static or adaptive, and as utilizing either global or local state network information.

4.3.1 Adaptive routing based on global information

Adaptive routing approaches increase the likelihood of establishing a connection by taking into account network state information. For the case in which global information is available, routing decisions may be made with full information as to which wavelengths are available on each link. In order to find an optimal route, a cost may be

assigned to each link based on wavelength availability, and a least-cost routing algorithm may be executed.

Adaptive routing based on global information may be implemented in either a centralized or distributed manner. In a centralized algorithm a single entity, such network manager, maintains complete network state information, and is responsible for finding routes and setting up lightpaths for connection requests. Since a centralized entity manages the entire network, a high degree of coordination among nodes is not needed; however, a centralized entity becomes a possible single point of failure.

A distributed adaptive routing algorithm based on global information may be implemented in a number of ways. In a link state approach, each node in the network must maintain complete network state information. Each node may then find a route for a connection request in a distributed manner. Whenever the state of the network changes, all of the nodes in the network must be informed. Therefore, the establishment or removal of a lightpath in the network may result in the broadcast of update messages to all nodes in the network. The need to broadcast update messages may result in significant control overhead, especially if lightpaths are being established and removed at high rate. Furthermore, it is possible for a node to have outdated information, and for the node to make an incorrect routing decision based on this information. We evaluate the above approach from several performance metrics later.

Another form of adaptive routing is *least-congested-path* (LCP) [16]. The congestion on a link is measured by the number of wavelengths available on the link. Links that have fewer available wavelengths are considered more congested. The congestion on a path is indicated by the congested link in the path. It has been shown in

[16] that using shortest-path routing first and LCP second for tie breaking works better than using LCP alone.

Although routing schemes based on global knowledge must deal with the task of maintaining a potentially large amount of state information which changes constantly, these schemes often make the most optimal routing decisions if the state information is up to date. Thus, global-knowledge-based schemes may be well suited to networks in which lightpaths are fairly static and do not change much with time.

4.3.2 Adaptive routing based on local information

Fixed alternate routing approach is the conventional local information based algorithm. In this approach, each node in the network is required to maintain a routing table that contains an ordered list of a number of fixed shortest routes to each destination node. Other than the static routing table, each node will only maintain information regarding the status of wavelength usage on its own outgoing links. Hence, there is no update messages in the network, and control bandwidth demand is greatly reduced. The routing scheme in this approach chooses from alternate paths on an end-to-end basis. When a connection request arrives, the source node attempts to establish the connection on each of the routes maintained in the routing table in sequence, until a route with a valid wavelength assignment (first-fit algorithm is used) is found.

Upon receiving a connection request, the source node sends a *PROB* message on the first stored shortest path toward the destination. This *PROB* message carries the set of free wavelengths along the first link of the path to be established. When the next hop receives that set, it intersects it with its own free wavelength set, and forwards the result to the next hop. If the final set is not empty, the last hop-router (destination) must pick one free wavelength from the resulting set, by using a wavelength assignment algorithm such as first-fit, configures its local node, and sends an acknowledgement, *RES* message, back to the previous hop with the chosen wavelength. Upon receiving an acknowledgement reservation message on a link L , the previous hop checks if the desired wavelength is in $F_{\lambda}(L)$; if it's, it removes it from $F_{\lambda}(L)$, configures its local node and passes the acknowledgement to its previous hop, until the reservation message is received by the first hop (ingress node).

If the resulting *PROB.FreeWave* is empty, a *NACK* message is sent back to the source node to indicate that the connection cannot be established on this path and the reserved resources are released. When the source node receives a *NACK* message, it performs RWA again and attempts to set up the connection on another stored route (second shortest path) and wavelength. If the second attempt fails, the connection is blocked.

Two local information based approaches are proposed in this chapter and we evaluate their performance from several metrics later.

4.4 The Network Modeled

In the network model considered here, IP/MPLS routers are attached to an optical core network. As shown in Fig. 4.1, the optical network consists of multiple optical cross-connects (OXC) interconnected via WDM links in a general mesh topology. The IP/MPLS routers are clients of the optical network and are connected to their peers over dynamically switched optical paths (lightpaths) spanning potentially multiple OXCs. The optical network essentially provides point-to-point connectivity between routers in the form of fixed-bandwidth circuits (lightpaths). The collection of lightpaths therefore defines the topology of the virtual network interconnecting IP/MPLS routers.

Each OXC can switch high-speed optical signals (e.g. OC-48, OC-192) at a given wavelength from any input ports to any output ports. The switching fabric can be purely optical or electrical or a combination of the two. In this work, we assume that the switching fabric is purely optical and that none of the OXCs have wavelength conversion capability (all-optical wavelength-conversion is an immature/expensive technology). Hence, to meet a connection request, a lightpath, that uses the same wavelength on all the links along the entire route from source-to-destination, has to be set up.

Each node consists of an OXC controlled by an electronic controller (IP router). The router is responsible for all management functions, including the management of optical resources, configuration and capacity management, addressing, routing, topology discovery, traffic engineering, and survivability. In general, the router may be traffic

bearing, or it may function purely as a controller for the optical layer and carry no IP data traffic [4]. In this work, it is assumed to function purely as a controller for the optical layer and carry no IP data traffic. The electronic controllers communicate with each other over a control network, either out-of-band, or in band. We assume the existence of a reliable transport protocol within the control network to ensure that messages between controllers are delivered reliably in sequence.

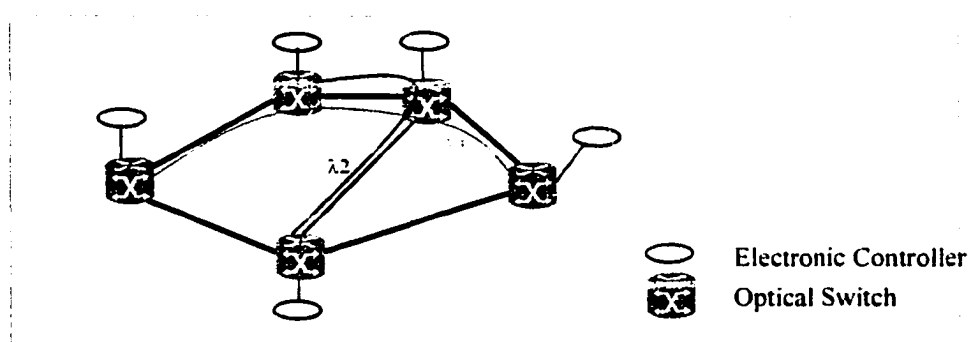


Figure 4.1. A wavelength-routed WDM network.

The Electronic Controller keeps a connection switch table that indicates the setting of its switches and the connection-id of the connections that use them. Also it maintains the status of every wavelength on every link emerging from that node. For a wavelength λ_i on link L the state can be one of the following:

- *RESERVED*: indicates that λ_i is being used in some connection to transmit data.
- *FREE*: indicates that the wavelength λ_i is available and can be used to establish a new connection.

For the link, L , the set of wavelengths that are in *FREE* state is denoted by $F_{\lambda}(L)$. When a wavelength, λ_i , is not in $F_{\lambda}(L)$, an additional field, *CID*, is needed to identify the connection request using λ_i . In this case, λ_i is in the *RESERVED* State.

Performance Metrics:

In a traditional computer network, most of the routing algorithms tend to minimize the propagation delay or the routing distance for a single connection [12].

To optimize the global performance of a real-time network, the following metrics are to be investigated:

- *Average Call Acceptance Rate (ACAR)*: the probability of accepting a real-time channel establishment (call) request, defined as the ratio of number of calls accepted to the number of calls arrived in the system.

$$ACAR = \frac{\sum_{i=1}^N Accepted(R)}{N}$$

- *Average Call Setup Time (ACST)*: the average time required to establish a connection once a connection request arrives.

$$ACSR = \frac{\sum_{i=1}^N Setup(R)}{\sum_{i=1}^N Accepted(R)}$$

- *Average Routing Distance (ARD)*: the average length of the established channels.

$$ARD = \frac{\sum_{i=1}^N Dist(R)}{\sum_{i=1}^N Accepted(R)}$$

- *Bandwidth Requirement for Control Messages*: when a connection is setup or released, control packets must be transmitted to the appropriate nodes.

Here, for an accepted call request R, we define the following variables:

- $Accepted(R) = 1$
- $Setup(R)$ = Time required to establish the connection R.
- $Dist(R)$ = Length of the path (in terms of Km) chosen for R.

For a call request R that is rejected, all above variables equal to zero. Let "N" be the total number of call-requests generated.

The first metric is very important, as it is a measure of the call throughput. The second metric is crucial in terms of real-time and interactive multimedia applications, which require fast channel setup. The third metric is essential because a shorter route is less costly.

4.5 The Proposed Routing and Signaling Algorithms

In a distributed signaling scheme, a lightpath is established by sending a connection request message from the source node to the destination node and by reserving the appropriate resources along the selected route.

4.5.1 Probe Flooding-Based Routing Algorithm (PFBR; Local Information Based)

Upon receiving a connection request, the source node sends a PROB message to all (or some) of its neighbors. The PROB message initially contains: the connection request ID, the destination node address, the set of free wavelengths along the link connecting the source node to the neighbor node (if the set is empty the PROB message is not sent) and an empty path list.

When an intermediate hop receives a PROB message, it forwards the PROB message to all (or some) of its neighbors, and it expects the node from which the packet has come, to find a qualified route. Before forwarding a PROB message to a neighbor, two tasks have to be accomplished: First, the node has to intersect the set of wavelengths of the incoming PROB message with the free wavelength set on the link (connecting the intermediate node to the corresponding neighbor) if the resulting set is empty the PROB message is not forwarded. Second, it has to check that the PROB message doesn't pass the same node more than once (to prevent loops).

The destination node might receive several copies of the PROB message, each containing different path list. It (the destination) must choose one of the paths according to some given selection criteria. Then, it picks one free wavelength from the resulting set.

by using a wavelength assignment algorithm such as first-fit or random selection, configures its local node, and sends an acknowledgement, *RES* message, back to the previous hop with the chosen wavelength. Upon receiving an acknowledgement reservation message on a link L , the previous hop checks if the desired wavelength is in $F_\lambda(L)$, and if it's, it removes it from $F_\lambda(L)$, configures its local node and passes the acknowledgement to its previous hop, until the reservation message is received by the first hop (source node).

It is possible that wavelength contention might occur since the distributed control scheme is used. In this situation, a *NACK* is sent to the source node to inform it of the failure on this route, and *NACK_RES* is sent to the destination node to release the wavelength previously reserved by the corresponding *RES* message. Once the destination node receives the *NACK_RES* message, and if it's already received a succeed *PROB* message on another route, it sends another connection reservation message towards the source node on that path. If the reservation succeeded, the connection is established. The source node is also responsible to send a *TEARDOWN* message to release the connection.

For this algorithm, the destination node selects the path associated with the *PROB* control message that arrives first. Thus, the least delay path is selected. Note that if a second *PROB* message arrives for the same connection request, the destination node stores it until the upstream reservation on the selected route is confirmed (the same as MPR-FCFS). In case if the upstream reservation fails, the destination node can use the stored second route instead.

This routing algorithm deflects control packets in order to find an available path for setting up a circuit-switched connection. A notable advantage of this routing approach is that it does not require the nodes to maintain any global information, and only requires local state updates; thus there is no need for a link state advertisement protocol. At the same time, the approach does not rely on a fixed set of routes, thereby providing a flexible routing strategy.

4.5.2 Multiple-Path Routing algorithm (MPR; Local Information Based):

Each node maintains a routing table that contains a list of a number of fixed routes to each destination node. For simplicity, we will only consider the case of the first two shortest-path routes for a given destination at each node. The algorithm can easily be extended to the case of more than two routes.

Upon receiving a connection request, the set of routes connecting the source-destination pair are searched in parallel. The source node sends a *PROB* message on each path toward the destination. This *PROB* message carries the set of free wavelengths along the first link of the path to be established. When the next hop receives that set, it intersects it with its own free wavelength set, and forwards the result to the next hop. If the final set (*PROB.FreeWave*) is not empty for both routes, the last hop-router (destination) must choose one of the available routes according to some given selection criteria. Then, it picks one free wavelength from the resulting set, by using a wavelength

assignment algorithm such as first-fit or random selection, configures its local node, and sends an acknowledgement, *RES* message, back to the previous hop with the chosen wavelength. Upon receiving an acknowledgement reservation message on a link *L*, the same steps of algorithm PFBR in section 3.1 are repeated.

If the resulting *PROB.FreeWave* is empty, a *NACK_PROB* message is sent back to the source node to indicate that the connection cannot be established on this path. The connection request fails only if the source node receives two (two routes are searched in parallel) *NACK_PROB* messages. That indicates that the connection request failed on all the possible routes.

4.5.2.1 Path Selection Schemes

The two path selection schemes considered here are:

A. First come first serve path selection (FCFS):

In this scheme, the destination node selects the path associated with the *PROB* control message that arrives first. This selection criterion is based on the assumption that the first packet to arrive is most likely the one that has taken the least delay path and, hence, is the one that encounters the minimum delay. If another successful *PROB* message arrives for the same connection request, the destination node stores it until the upstream reservation on the first selected route is confirmed. The stored route can be used in case if the upstream reservation fails. On the other hand, if the *PROB* message has

arrived after the upstream reservation has already been confirmed, the destination node discards this message. This path selection scheme minimizes the connection setup time for a connection request. The destination node doesn't have to wait for the arrival of the second *PROB* message to decide on a path to setup the connection request.

B. Least-congested path selection scheme (LCP):

In this scheme, the path with the maximum number of common available wavelength (*PROB.FreeWave*) is selected to setup the connection. In this case, the destination node has to wait until both *PROB* messages are received (or until a timeout expires after the reception of the first one, or a *NACK* message is received on the second path after the reception of a *PROB* message on the first path). If two paths with different hop counts have the same average number of available wavelengths, the smaller hop-count one is chosen. *LCP* scheme distributes the traffic evenly in the network. Smooth traffic is carried on each link. As will be shown below, multi-path routing with least-congested path selection scheme improves network performance compared to alternate shortest-path routing. A variant of *LCP* have been proposed in [14] which only examines the first *k* links of each paths, and the source node makes both path and wavelength selections.

4.5.3 Link state Approach (Global Information Based)

In a link state approach [10], each node in the network must maintain complete network state information, including the network topology and wavelength usage on each

link. Based on this global information, the source node can calculate an optimum route to a destination on a given wavelength. In this work, we have used the RWA scheme proposed in [5, 8] where both the routing and wavelength assignment sub-problems were integrated and collapsed into a single dynamic constraint-based routing problem. Once the route and wavelength are selected, the source node then attempts to reserve the selected wavelength along each link in the route by sending a separate reservation requests in parallel to each node in the route. Each request is routed on the shortest path.

If an intermediate node is able to reserve the wavelength on the appropriate link, it sends an acknowledgement directly back to the source node. If all of the reservations are successful (the source node receives positive acknowledgements from all nodes along the route), the source sends a SETUP message to each of the nodes. The appropriate switches are then configured at each node, and the connection is established. If only one of the reservations is not successful, then the call is blocked and the source node sends a TAKEDOWN message to each node in the route in order to release the reserved resources. The advantage of parallel reservation scheme is that it shortens the lightpath establishment time by having nodes process reservation requests in parallel. The disadvantage is that it requires global knowledge, since both the path and the wavelength must be known in advance.

Whenever the state of the network changes, all the nodes must be informed. In other words, all nodes must maintain a synchronized and identical topology and link state information (traffic-engineering database). Therefore, the establishment or removal of a

lightpath in the network may result in the broadcast of update messages to all nodes in the network. Broadcasting these update messages can be triggered either periodically or based on a given threshold criterion as follows:

1. Periodical topological update:

In this case, periodically (when UPDATE-TIMER expires) and whenever there is a change in the switch table, each node broadcasts information to all other nodes. A topological update message contains the list of up links adjacent to the node and their wavelength usage. Every node in the network maintains a topology database that reflects its knowledge of the nodes that are up, the highest timestamp of update messages received from each such node, the links that are up next to each node and their wavelength usage. Whenever a node receives an update message about another node with a later timestamp than the stored one, it updates the corresponding information and propagates it by sending the update message to all neighbors.

2. Threshold topological update:

In this case, a topological update message is generated if the number of changes on a link originating from that node is equal to certain threshold. The threshold criteria used here is the number of wavelength that their status change per link. The topological update message contains the same information as in the case of periodical topological update. Note that the signaling overhead associated with the link state updates for this scheme is considerably less than that of periodical update.

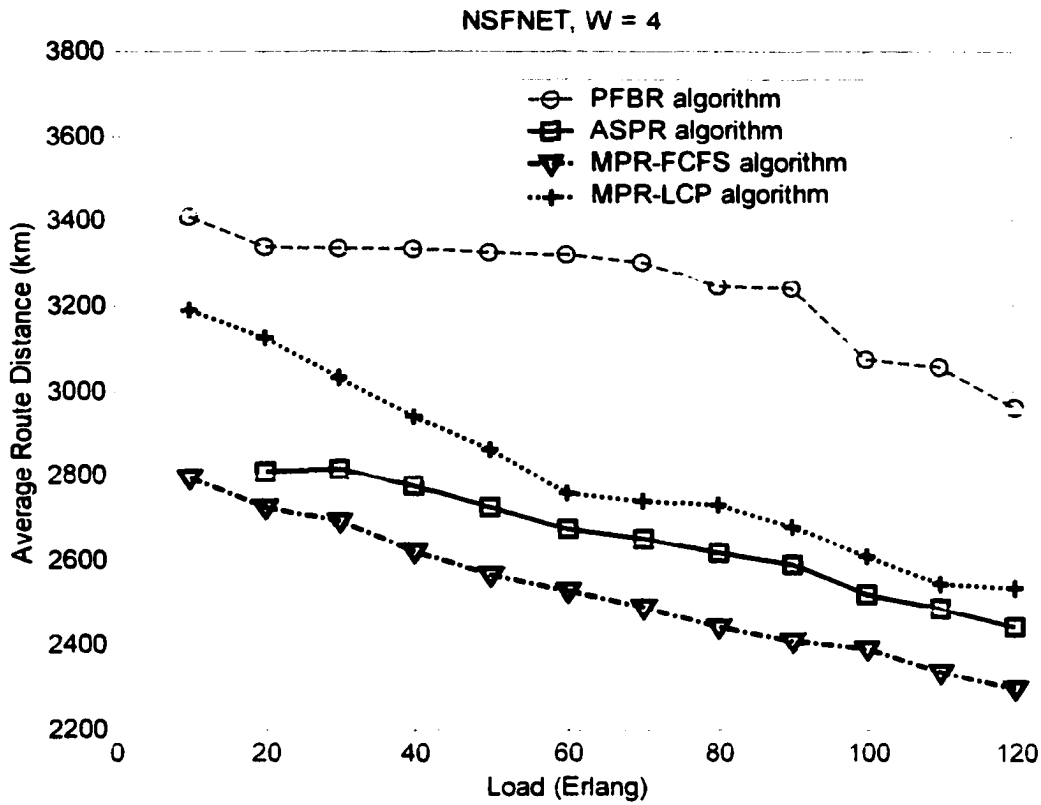


Figure 4.3. Average Route Distance versus load.

A: Average Routing Distance (ARD):

Fig. 4.3 shows the ARD versus load for the three algorithms: 1) the proposed MPR algorithm in terms of its two versions of the path selection schemes (FCFS and LCP), 2) the proposed PFBR algorithm, and 3) the conventional alternate shortest-path routing (*ASPR*) algorithm [5]. PFBR algorithm keeps the longest ARD while the MPR-FCFS has the shortest ARD among all the algorithms under all scenarios. This is because in the case of the MPR-FCFS approach, a set of fixed paths (2 in this chapter) is searched in parallel, and the shortest path is always selected if it's available. In MPR-LCP approach, the least congested path is selected, which can be the longer path in most cases. On the other hand, in PFBR algorithm, there is an excessive search for paths: the approach does not rely on a fixed set of routes and the possibility of selecting long paths

are higher. From figure 4.3, we can also see that ARD linearly decreases as the traffic load increases. The reason is that for the simulated network topology, almost of all shorter paths (in distance) have the fewer hops than the longer paths, hence, as the load increases, the shorter paths are more favorable than the longer paths, i.e. a connection, which spans more hops, is more likely to be blocked than the connection that spans fewer hops under wavelength continuity constraint.

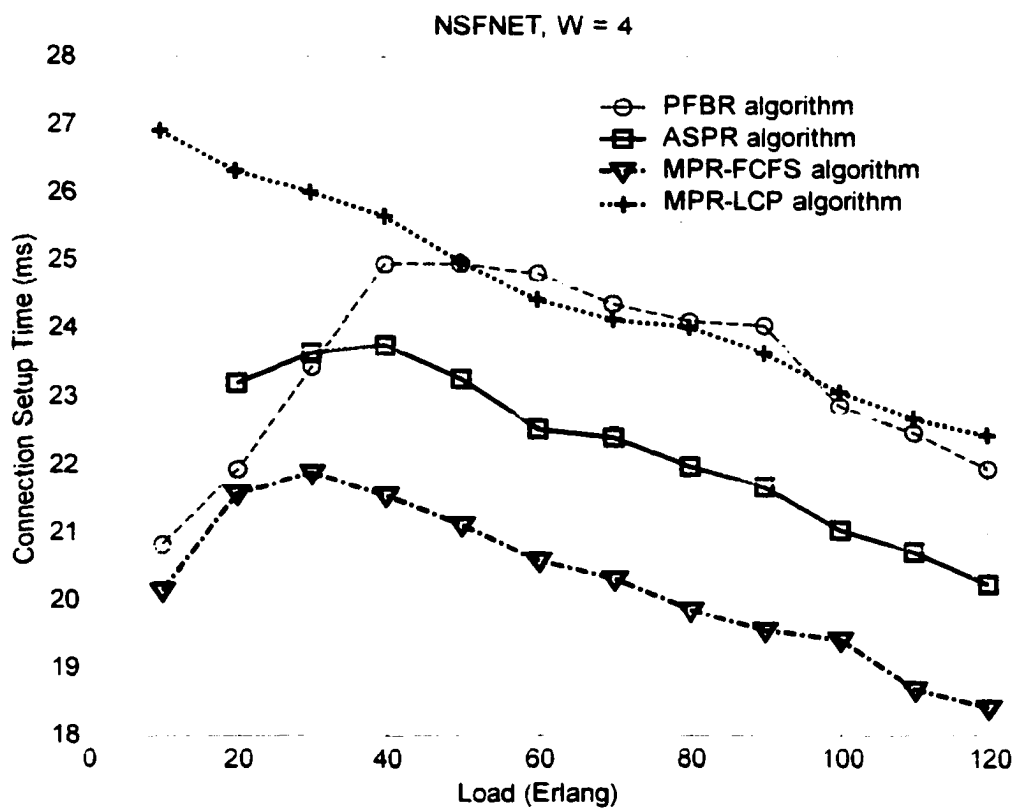


Figure 4.4 Connection Setup Time versus load.

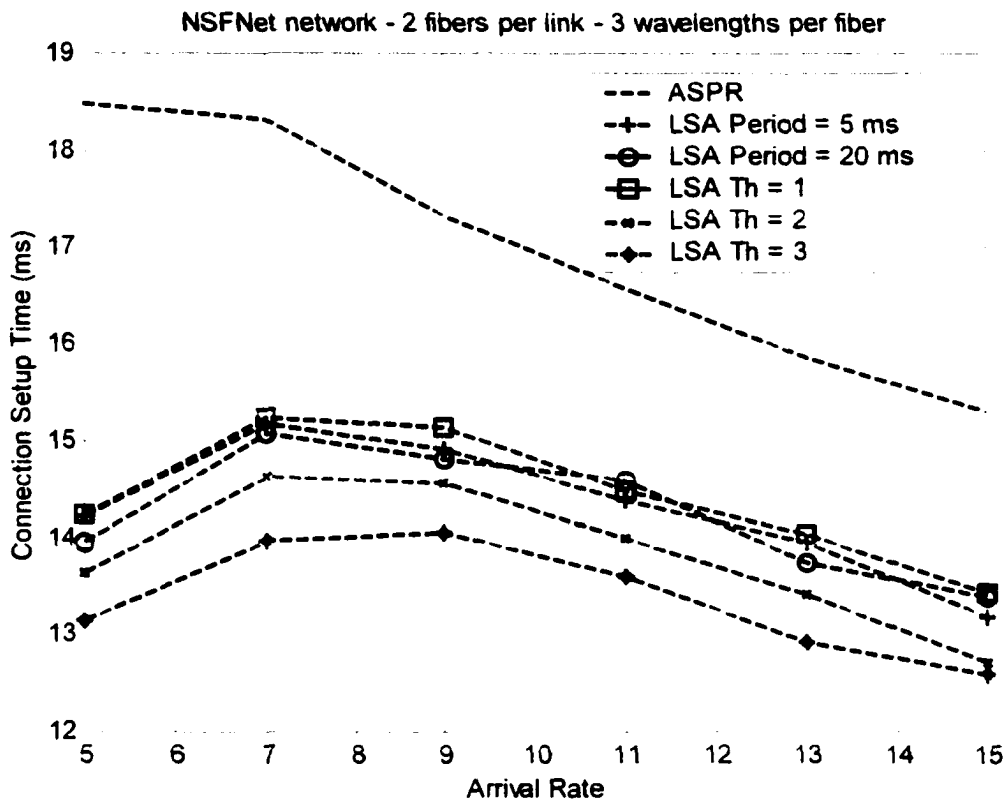


Figure 4.5: Connection setup time versus arrival rate

B: Average Connection Set Up Time (ACST):

Figure 4.4 plots ACST versus load for three algorithms. It's very interesting to observe that at lower load (less than 30 Erlangs), except MPR_LCP, the ACST in all other algorithms increases when the load increases. This is because, when the load increases, the shortest path may become unavailable, the longer paths must be used. However after a certain traffic load, ACST decreases as the traffic load further increases, we can use the conclusion in Figure 4.3 to explain this.

Figure 4.5 plots the connection setup time vs. load in NSFNET, for the link state approach (with different update procedure schemes) and for the alternate shortest path

approach. As the load increases, the shortest paths may become unavailable, and longer paths must be selected. Therefore, the connection setup time may increase as load increases.

It is interesting to observe that the link state approach (all the update procedure studied) gives lower connection setup time than the alternate shortest path approach. In ASPR approach the OXC has to always choose between static routes (with disjoint links) connecting source to destination. However, in the link state approach, the route is calculated online based on the global view of the network, and that leads to shorter paths between the source and the destination.

Figure 4.5 shows that LSA approach with non-periodic update procedure in the case of threshold is 3 gives the lower connection setup time, this because the node doesn't have an up-to-date view of the network, so the connection that spans more hops are more likely to be blocked.

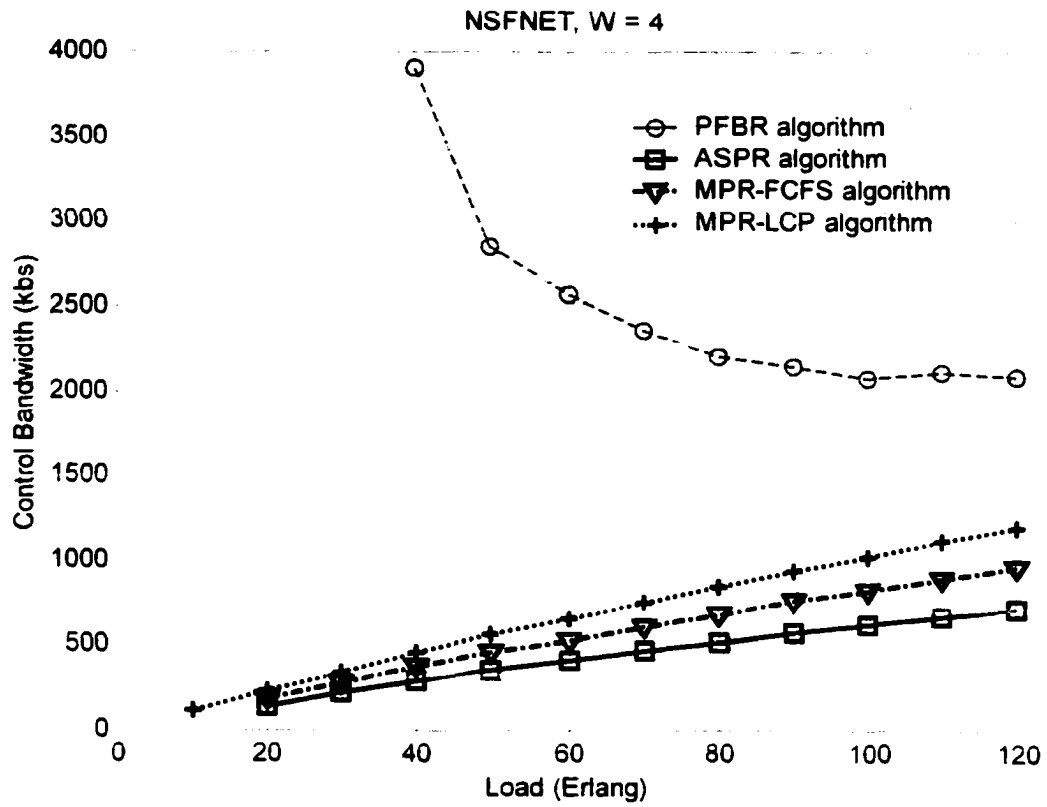


Figure 4.6. Bandwidth requirement of control messages.

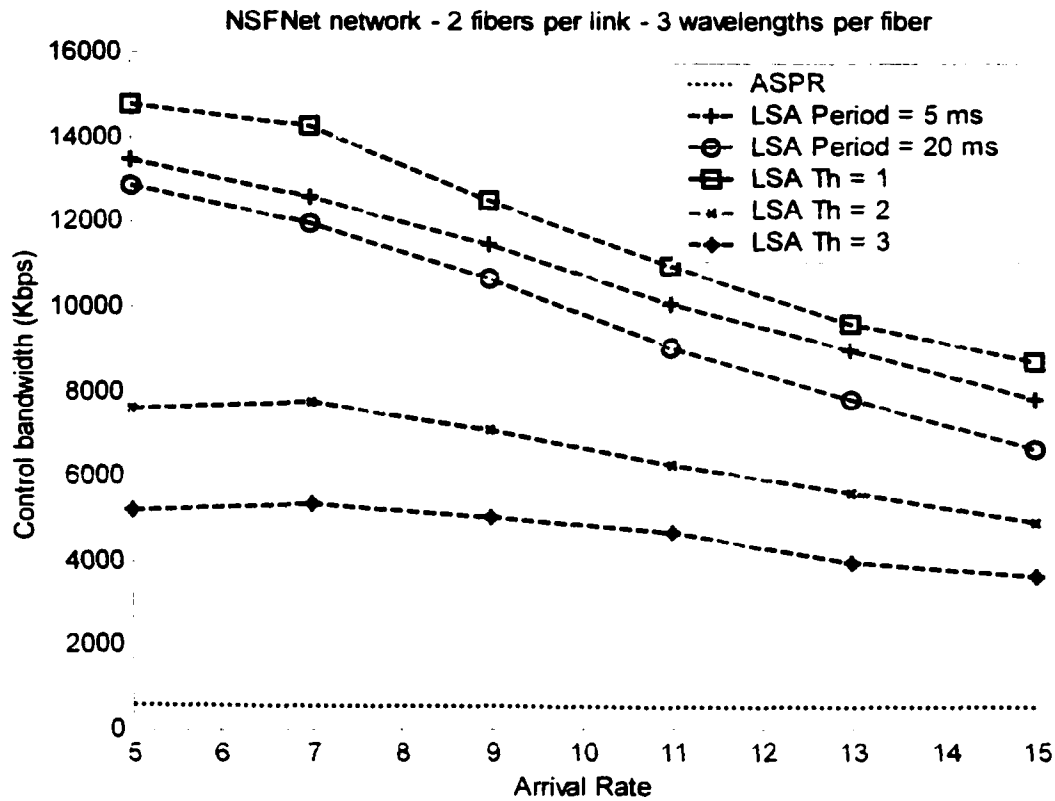


Figure 4.7: Bandwidth requirement of control messages versus arrival rate

C: Requirement for control bandwidth

We define the size of the control message as a function of the network size. This is because each control message contains information about connection source, connection destination, wavelength vector, and path vector of the connection. For a network with N nodes, we assume that the size of a control message for all approaches is $s_c = N + 4$ bytes.

Figure 4.6 illustrates the relationship between the control message bandwidth requirement and traffic load for different routing schemes. As expected, the PFBR

algorithm has largest bandwidth requirement since control messages (PROB messages) are sent to all over the network. However, in PFBR, as the traffic load increases, the more network resources are consumed, the more opportunity there is that the PROB messages get dropped in the intermediated node is, thus the bandwidth of control messages decreases exponentially.

Figure 4.7 illustrates the relationship between the control message bandwidth requirement and the traffic load for the ASPR and LSA routing schemes. The control bandwidth required by the ASPR approach is negligible compared the LSA approach and this is obvious since there is no LSA flooding in ASPR approach. It's been shown that in the case of threshold update procedure the control bandwidth required is significantly less than in the case of periodic update procedure, and it shows almost the same performance in term of number of calls accepted. With threshold update procedure, an LSA is only generated and flooded to the network when the number of changes on a link is equal to a threshold delta. In the case of periodic update, an LSA is flooded only if a change in the network occurs, and that explains why the control bandwidth is almost the same when the period is 5ms and when the period is 20 ms.

D: Blocking Probability/ACAR

Figure 4.8 shows the blocking probabilities versus traffic load. PFBR algorithm is superior in terms of ACAR compared to all other algorithms. The reason behind that is the excessive search for a path without a restriction to a fixed set of paths. Multiple-path routing with least-congested path (MPR-LCP) selection scheme outperforms the MP-

FCFS and ASPR approaches. One of the reasons is that MPR-LCP distributes the traffic evenly in the network, so it can accommodate more traffic.

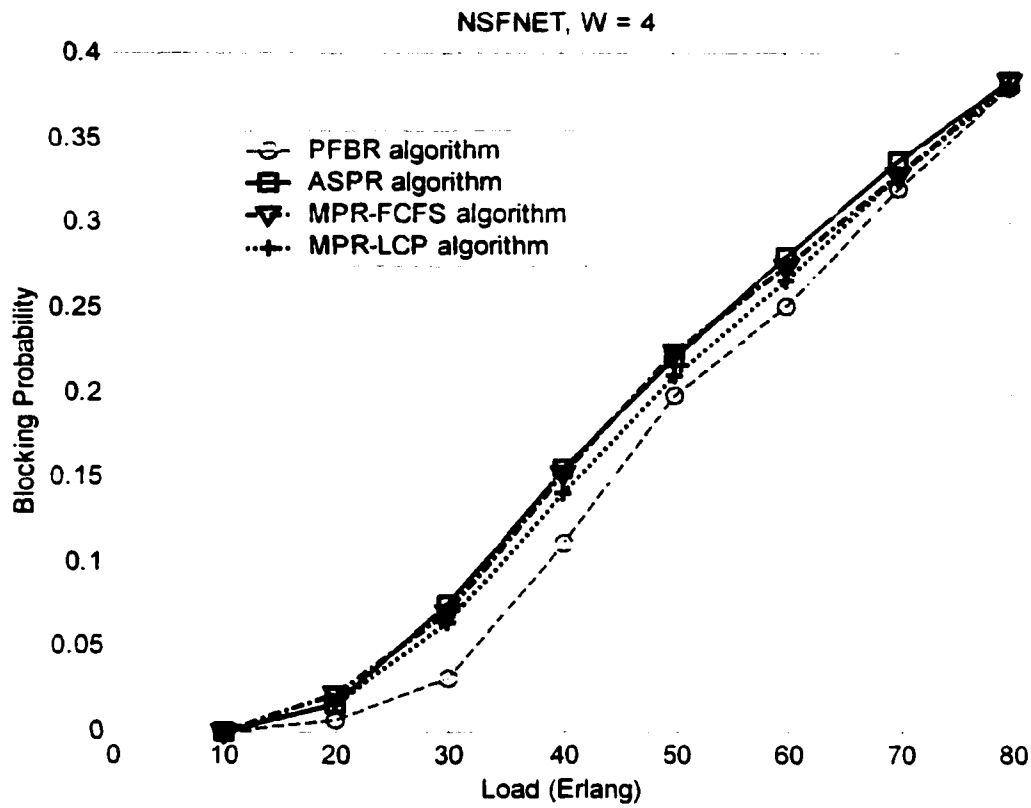


Figure 4.8 Blocking probability versus load

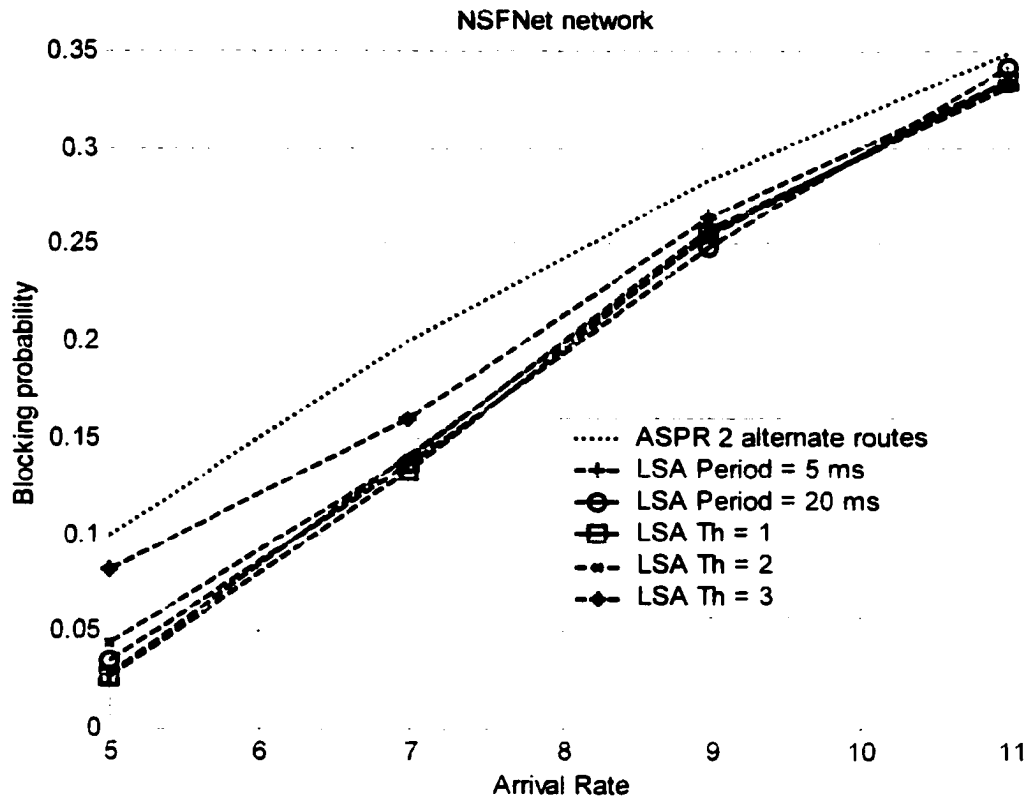


Figure 4.9: Blocking probability versus load

Figure 4.9 shows the blocking probabilities versus traffic load for ASPR and LSA routing schemes. As shown in the figure, the ASPR shows the worst performance at low load. The LSA with threshold update (threshold equal the number of fibers per link shows the best performance) bases shows almost the same performance as the periodic update based with significantly lower control bandwidth.

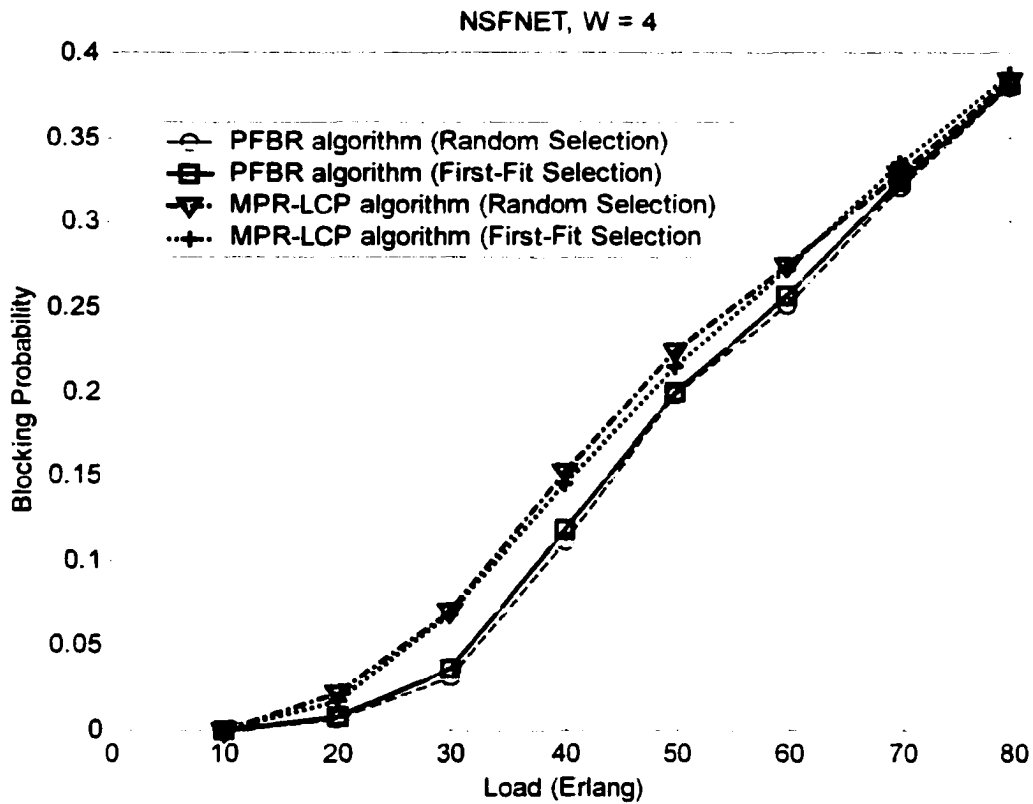


Figure 4.10 Blocking Probability for different wavelength selection policy.

E: Wavelength Assignment

We also studied the effect of the wavelength selection policy (shown in Figure 4.10). A random selection policy and a first-fit policy were investigated. Simulation results show that a random selection policy performs better than a first-fit policy. In a first-fit approach, two simultaneous connection requests are more likely to compete for the first available wavelength since the distributed control environment is adopted in our simulation.

4.7 Conclusion

This work has proposed two new distributed signaling protocols for fast automatic setup and tear-down of paths across the emerging interconnection models for IP-over-optical- networks. The first scheme is probe flooding-based routing (PFBR) algorithm with backward reservation while the second scheme is based on an adaptive routing algorithm called *Multi-Path Routing (MPR)* where k paths are probed simultaneously. Time discrete simulation tool has been developed to examine the effectiveness of the proposed algorithms in terms of call acceptance rate (CAR), call set-up time (CST), average routing distance (ARD), and bandwidth required for control messages. The simulation results have revealed that the proposed PFBR algorithm is superior in terms of CAR at the cost of ARD, CST, and bandwidth requirements for control messages, whereas the MPR-FCFS offers the lowest CST and ARD at the expense of CAR.

Also this work has investigated and compared the performance of two GMPLS-based distributed control and management protocols for dynamic lightpath provisioning in future IP networks. The first protocol is a global information-based link state approach that consists of both an integrated RWA algorithm and a signaling algorithm. Two triggering mechanisms for the LSAs update procedures are considered; one is periodically-based and the other is threshold-based update. The second protocol is a local-information based fixed alternate link routing approach where the signaling protocol is closely integrated with the RWA protocols. The performance of the two protocols is compared in terms of three metrics, namely, (a) connection setup time, (b)

blocking probability, and (c) bandwidth requirements for control messages. It is shown that the global information-based link state approach with both its LSAs triggering mechanisms outperforms the local information-based fixed alternate link routing approach in terms of blocking probability and connection setup time; but it requires more signaling overhead. It has also been shown that threshold update triggering mechanism outperforms the periodical update triggering mechanism in term of connection setup time. Furthermore, it requires significantly less control signal overhead.

Chapter 5

5. Distributed Connection Management Protocol for Survivable WDM Optical Networks

5.1 Introduction

One of the most important considerations of a carrier in designing and deploying its transport network is the reliability offered by the network to the services and customers it supports. Service reliability considerations are profoundly critical when high capacity wavelength division multiplexing (WDM) transport technologies are involved, since certain single WDM transport system failures may affect millions of connections [1,2].

The challenge, then, is to make the optical network consisting of optical cross connects (OXC)s, dense wavelength division multiplexers, and optical add/drop multiplexers (OADMs) dynamic and intelligent. A major aspect of this intelligence is fast provisioning and restoration [3,4]. The optical network must ensure satisfaction of stringent service level agreement that mandates very high levels of customer connectivity, even in the face of major facility failures.

Connection protection and restoration schemes are used to recover connectivity in the face of service affecting network failures. In the majority of these schemes, a connection is defined by two end-to-end paths – one for the service (primary) and one for restoration (backup). Protection schemes establish the backup path before service path failure where backup resources are pre-computed and reserved in advance. Such mechanisms, while minimizing the service restoration time, require dedicated resources on both the primary and backup paths. For most applications, this bandwidth inefficiency is simply too costly. Significant improvements in resource utilization can be achieved by instead using restoration schemes, where the restoration path is established only after the service path fails. Thus, a restoration scheme does not rely on pre-provisioned resources but instead, dynamically compute new routes and assign wavelengths to effectively re-route the affected traffic after link or node failure.

Strategically, there are two categories of restoration schemes: end-to-end path-based and local or link-based. Path-based schemes typically provide node and link disjoint alternate paths for every restorable connection in the network. Local or link-based schemes provide many locally disjoint alternate paths that can collectively cover all the failures along the primary route. It is well known that in general path-based restoration schemes require less network capacity than local or link-based restoration schemes. The latter is especially inferior when we want to provide 1+1 restoration over diverse paths.

In this chapter, we present a novel, fast, and distributed connection management protocol

with rerouting capabilities for optical layer restoration in general mesh-type optical networks. We introduce a novel concept of a “token-based” distributed rerouting protocol to reroute existing connections to optimal paths after the failure recovery. The goal is to protect each connection from single-link failures, as well to minimize the overall blocking probability and the restoration delay. The performance of the proposed algorithms is evaluated and compared via simulation in a distributed control environment.

We employ both link-based and path-based restoration schemes to examine the applicability of the proposed approach over several performance metrics in a distributed environment. The traffic pattern considered here is dynamic where connection requests arrive one at a time and each connection exists for only a finite duration, called the connection-holding time. Given a fixed number of wavelengths on each fiber link, our objectives are: a) to minimize the overall call-blocking probability, b) to minimize the average end-to-end connection setup time, and c) to minimize the restoration delay after a link or node failure.

Specifically, the proposed control and management protocol provides the following capabilities:

1. Routing and wavelength-Assignment (RWA): upon the arrival of a connection request, the protocol must select a route from the source to the destination, and assign a wavelength to the selected route. If this process is not successful, the connection request is blocked;

2. **Signaling:** After the routing and wavelength assignment is completed, the protocol signals the appropriate nodes to reserve the wavelength on requested links and configure their switches.

3. **Fault-Detection:** if a link failure occurs, the end nodes of the failed link (which is unidirectional fibers, going on opposite directions) must be able to detect the failure; and those which detect the failure must notify the end nodes of the connections which are going through the failed link that a failure has occurred;

4. **Fault-Recovery:** A backup path must be calculated to every interrupted connection. then signal the nodes in the calculated backup paths to reserve the wavelength on selected links and configure their switches.

5. **Rerouting / Non- Rerouting:** after the failure, the existing connections are restored on longer paths, and the new incoming connections may not be routed on their optimal paths (if the optimal path includes the failed link). After a fixed period of time, the failure is repaired and all the wavelengths on the repaired link are available. The nodes will try to reroute the exiting connections to their optimal routes. Signaling is then needed to tear down the rerouted connections and switch them to their shorter paths. In the case of non-rerouting restoration, all the connections remain in place.

6. **Link state update:** the mechanism must also be able to provide updates to reflect which wavelengths are currently being used on each link so that nodes may make routing decision based on up-to-date information.

The rest of this chapter is organized as follow. In Section 2, we describe the architecture of our network model. In section 3, we propose our control and management protocol. Section 4 presents numerical results for restoration schemes on a representative network topology. Section 5 concludes this work with a discussion of its main contribution

5.2 Network Architecture

In the network model considered here, IP/MPLS routers are attached to an optical core network. The optical network consists of multiple optical cross-connects (OXCs) interconnected via WDM links in a general mesh topology. The IP/MPLS routers are clients of the optical network and are connected to their peers over dynamically switched optical paths (lightpaths) spanning potentially multiple OXCs. The optical network essentially provides point-to-point connectivity between routers in the form of fixed-bandwidth circuits (lightpaths). The collection of lightpaths therefore defines the topology of the virtual network interconnecting IP/MPLS routers.

Each OXC can switch high-speed optical signals (e.g. OC-48, OC-192) at a given wavelength from any input ports to any output ports. The switching fabric can be purely optical or electrical or a combination of the two. In this work, we assume that the switching fabric is purely optical and that none of the OXCs have wavelength conversion capability. Hence, to meet a connection request, a lightpath, that uses the same wavelength on all the links along the entire route from source-to-destination, has to be set up.

The router (IP/MPLS) is responsible for all management functions, including the management of optical resources, configuration and capacity management, addressing, routing, topology discovery, traffic engineering, and survivability.

In general, the router may be traffic bearing, or it may function purely as a controller for the optical layer and carry no data traffic.

In this work, it is assumed to function purely as a controller for the optical layer and carry no IP data traffic. The routers communicate with each other over a control network, either out-of-band, or in band. We assume the existence of a reliable transport protocol within the control network to ensure that messages between routers are delivered reliably in sequence.

The IP/MPLS router keeps a connection switch table that indicates the setting of its switches (incoming and outgoing ports) and the connection-id (a unique identifier in the network for a connection) of the connections that use them. Also it maintains the status of every wavelength on every link in the network.

When a connection is established or taken down, each node involved in the connection broadcasts a topology-update message which indicates any changes in the status of wavelengths being used on the node's outgoing links [7,8].

5.3 Proposed Protocol Description

A link state protocol is used to keep up-to-date information at each node of the network. Each node maintains the complete network topology, including information about the wavelengths that are in use on each link.

Based on this global information, the source node can calculate an optimum route to a destination on a given wavelength. In this work, we have used the RWA scheme proposed in [9] where both the routing and wavelength assignment sub-problems were integrated and collapsed into a single dynamic constraint-based routing problem. Once the route and wavelength are selected, the source node then attempts to reserve the selected wavelength along each link in the route by sending a separate reservation requests in parallel to each node in the route. Each request is routed on the shortest path.

If an intermediate node is able to reserve the wavelength on the appropriate link, it sends an acknowledgement directly back to the source node. If all of the reservations are successful (the source node receives positive acknowledgements from all nodes along the route), the source sends a SETUP message to each of the nodes. The appropriate switches are then configured at each node, and the connection is established. If only one of the reservations is not successful, then the call is blocked and the source node sends a TAKEDOWN message to each node in the route in order to release the reserved resources. The advantage of parallel reservation scheme is that it shortens the lightpath establishment time by having nodes process reservation requests in parallel. The disadvantage is that it requires global knowledge, since both the path and the wavelength must be known in advance.

Whenever the state of the network changes, all the nodes must be informed. In other words, all nodes must maintain a synchronized and identical topology and link state information (traffic-engineering database). Therefore, the establishment or removal of a lightpath in the network may result in the broadcast of update messages to all nodes in the network. Broadcasting these update messages can be triggered either periodically or based on a given threshold criterion: *Periodical topological update or Threshold topological update* [10]. It has also been shown that threshold update triggering mechanism outperforms the periodical update triggering mechanism in term of connection setup time and overall call-blocking. In this chapter we use the Threshold topological update mechanism.

5.3.1 Fault Detection and recovery:

Each link is bi-directional with a pair of unidirectional fibers going on opposite directions. Usually, these two fibers reside in the same cable and they get cut at the same time. Before a link cut, there are either some traffic going through that link or probing data in some special patterns just for keeping the line “alive” instead of “idle”. When there is a cut, the downstream node (both end nodes will be downstream as well as upstream if the link is bi-directional) of this link will detect the failure. And it will notify each source node whose connections are going through this fiber about the failure.

In path-based restoration scheme, the restoration algorithm is as follows:

The nodes adjacent to the failed link send LINK-FAIL messages to all the source and the destination nodes of all connections that traverse the failed link. As this message

improve throughput and reduce the over-all blocking probability as shown in the following section. To implement a smooth rerouting algorithm (prevent wavelength contention), we visualize a “token” which is created (by an edge node of the recovered link) after a link recovery and is passed from node to node. Whatever node has the token is allowed to reroute its exiting connections to optimal routes. Nodes with nothing to reroute are obligated to pass the token on rather than saving it. A token is discarded when is passed to all the nodes in the network.

5.4 Performance Evaluation

The performance of the proposed adaptive algorithms is evaluated via simulation in a distributed control environment. Three metrics are used to evaluate the performance:

Blocking Probability: probability that a connection cannot be established due to resource unavailability or contention along the desired route.

Restoration Efficiency: is the ratio of the number of connections that are restored after the link failure to the total number of connections that traverse the failed link.

Restoration time: Time required to recover a connection when a failure occurs.

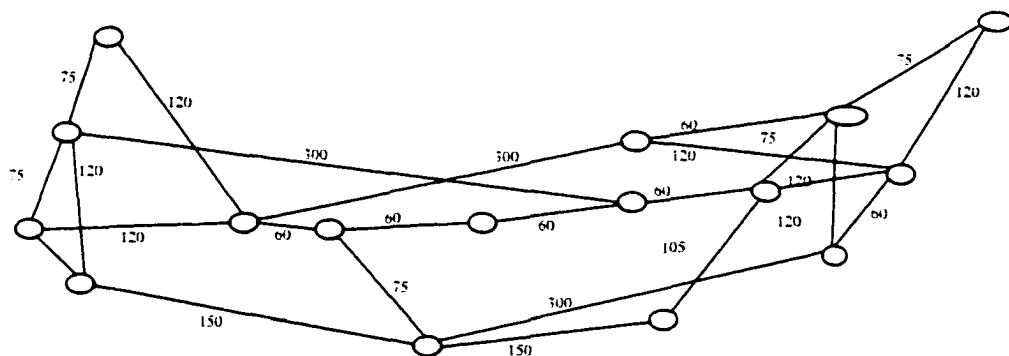


Figure 5.1: nation wide network

The performance of the proposed algorithm is evaluated via simulation of the mesh-based network shown in Fig. 5.1. The numbers on the links represent link distances in tens of kilometers. We assume that two adjacent nodes are connected by M bi-directional fibers ($M=2$ in our simulation). The number of wavelength per link is assumed to be eight. 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 $1/\mu = 30$ minutes. The load at each node is measured in Erlang λ/μ . We also assume that the processing time for a control message at each node is $10 \mu s$; the time to configure, test, and set up a cross-connect is $500 \mu s$. each data point is obtained over a simulation of 10^5 connection requests. Link-cuts occur at rate of 0.0025 cuts/ms and it takes 10 minutes to fix a link [8].

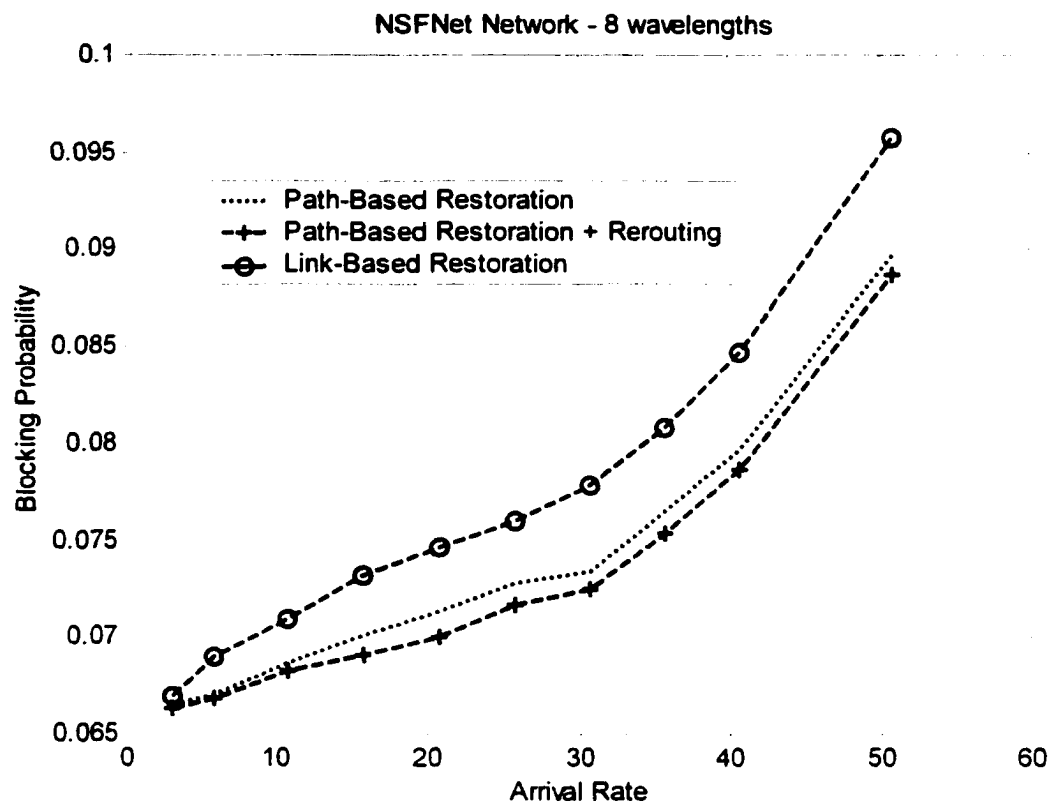


Figure 5.2: Blocking probability versus arrival rate

Figure 5.2 shows blocking probability versus arrival rate for link-based Restoration, path-based restoration and path-based restoration plus rerouting. We observe that a network with path-based restoration achieves better performance in term of overall blocking probability than a network with link-based restoration. Path restoration performs a search for backup path on an end-to-end basis (the backup path could possibly be on different wavelength), whereas link restoration is constrained to find backup paths around the failed link on the same wavelength as that the failed connections. As a result, with link restoration, the restoration paths are longer, the network resources are consumed, and the probability that a new connection will be blocked is higher.

Figure 5.2 also shows that a network with Rerouting achieves better overall blocking probability than a network without rerouting. And that is because; Rerouting provides better overall use of network resources, since connections are switched to optimal routes (can be the prior routes) as soon as the failure is recovered.

Figure 5.3 compares the restoration delay per cut in path-based and link-based restoration schemes. With current assumptions of message processing time and switch configuration time (NSFNET as simulation network), it takes less than 35 ms to recover a connection with link-based restoration scheme and less than 48 ms with path-based restoration scheme. Both are decent recovery speed compared with 50 ms for the 1:1 (1+1) self-healing SONET networks.

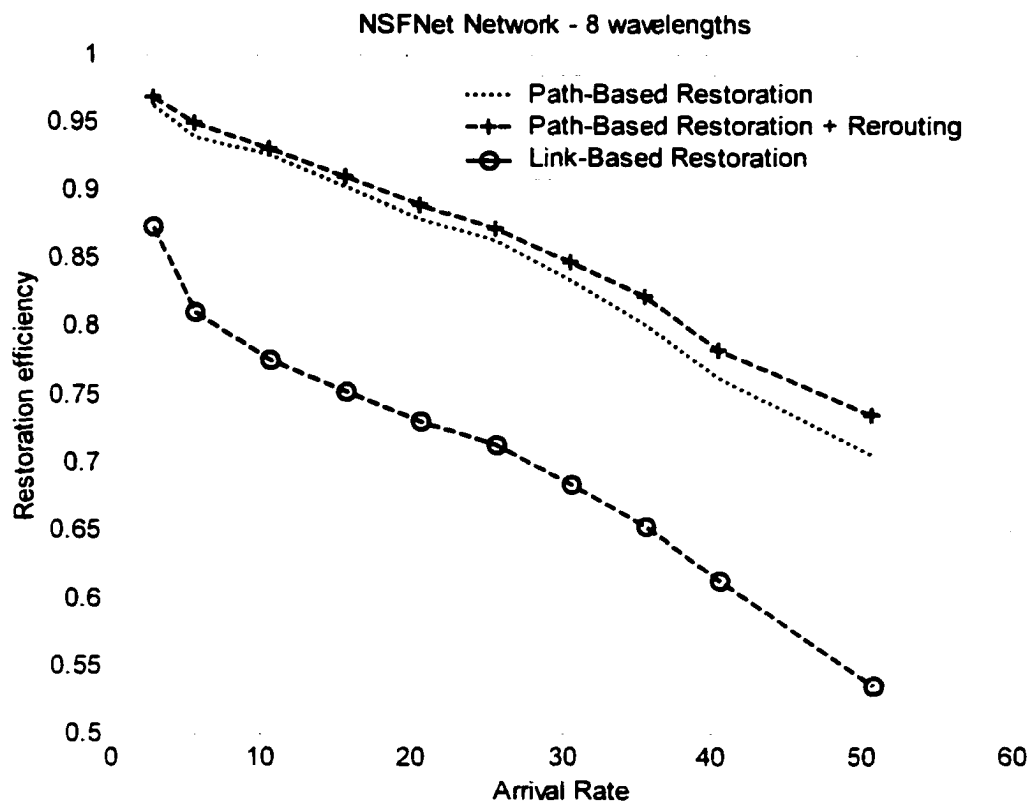


Figure 5.3: Restoration Efficiency vs. arrival rate

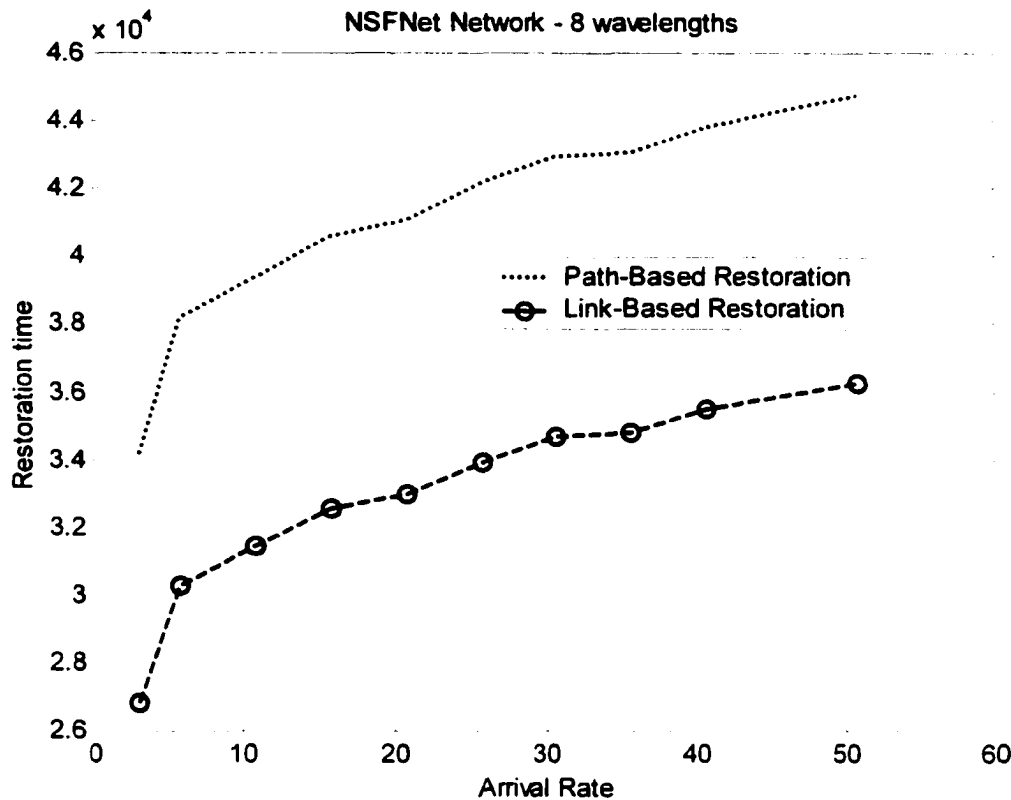


Figure 5.4: Restoration Time vs. arrival rate

Figure 5.4 illustrates the restoration performance of path-based and link-based restoration. As shown in figure 5.3 and 5.4, path-based has better restoration efficiency than link-based restoration, and link-based restoration has a better restoration time compared to path-based restoration. Path-based restoration performs a search for a backup path on an end-to-end basis (the backup path could be possibly on a different wavelength), whereas link-based restoration is constrained to find backup paths around the failed connections. As a result, the backup paths in link restoration tend to have fewer hops than the backup paths found in path-based restoration. Therefore link-based restoration has a better restoration time than path restoration. The restoration efficiency for path and link restoration decreases as the load increases because there are fewer spare wavelengths in the network.

5.5 Conclusion

In this chapter, we proposed an on-line control and management protocol for fast lightpaths provisioning and restoration. The proposed management protocol has RWA, signaling, link state update, fault detection and recovery, and rerouting capabilities. A new “Token-Based” distributed rerouting algorithm is proposed. Under our current assumptions of message processing speed and switch configuration time, the connection-recovery time in the NSFNET network (figure 1) when applying link-based, path-based, or path-based plus rerouting restoration schemes is under 50 ms. That is an acceptable recovery time. Also the simulation results show that the proposed rerouting algorithm improve the network throughput and reduce the overall blocking-probability.

Chapter 6

6. Analysis of Rerouting in Wavelength-Routed WDM Networks

6.1 Introduction

The basic idea of dynamic routing in wavelength routed WDM network is to increase throughput by routing calls to alternate paths when the direct path is blocked. However, the use of alternate paths usually consumes more network resources as the path in length, in hops, is usually longer. Therefore, indiscriminate use of alternate paths could lead to the decrease of the network throughput and even network instability, as many of the previous research studies had shown [1], [2], [3], [4].

In dynamic routing, a routing decision must be made at call-arrival time based on the network information available at that time. However, a decision once made is final. One method to increase the throughput of the traditional dynamic routing is to redistribute network load to eliminate traffic hot spots or bottlenecks. Rerouting is the practice whereby calls on alternate paths can be rerouted back to direct paths or to other less congested alternate paths as situation warrants.

Our purpose of rerouting is to redistribute network load from time to time so as to free up more capacity for direct path calls. For example, if a channel has just been freed

up in a link AC due to a call departure (Fig. 6.1), then a call on an alternate path (path ABC) can be rerouted back to link AC. Doing so would free up one wavelength each on links AB and AC and thus throughput can be increased. The focus of this chapter is on an original analysis of the Least Load Routing (LLR) based rerouting rule in a symmetrical fully connected network. This analysis is based on the Erlang fixed-point model first applied to state-dependent dynamic routing by Eric W. M. Wong et al.[6], in which LLR was analyzed. While significantly reducing the computational effort, the model was shown to be quite accurate.

Many versions of rerouting are possible [5]. Our focus is on a very simple one as follows. A new arriving call will be routed to its direct path X first if there is a free wavelength on that path. If path X is blocked, one alternate call on path X, if any, is picked up randomly and rerouted back to its direct path (if possible) to make room for the new call. If the rerouting on this alternate call is unsuccessful, another alternate call on path X is picked up at random and so on. If none of the alternate calls on path X can be rerouted, the overflow call is routed to a (two-link) alternate path with the maximum number of free wavelengths, i.e., the least loaded alternate path, as in LLR routing. If all alternate paths are full, the call is blocked.

6.2 Analysis of rerouting:

Consider an M-node fully connected network and uniformly loaded network where all links consists of N wavelengths. Let $n = (d, a)$ be the occupancy state of a link where d and a are the numbers of directs and alternate calls on a link, respectively. Let $P_n = P_{d,a}$ be the state probability. Let λ_D be the rate of direct path offered traffic to a link and λ_O be the rate of overflow traffic from a link to other links. Let both these traffic streams be Poisson processes and let the call service time be exponentially distributed with mean equal to one time unit. We restrict our choices of alternates paths to those of two links only and let m be the number of two-link alternate paths. Note that m is a system selection parameter and the maximum value of m is $M-2$ for the fully connected network. For $m < M-2$, intermediate nodes of overflowed paths are selected at random. The resulting network is, therefore, still symmetrical. It is well known that, if no suitable control is taken, the number of alternate path calls may dominate, resulting in significant reduction of network capacity. It is also well known that trunk reservation, i.e., reserving the last r unoccupied wavelengths in a link for direct-route calls only, is an effective means of maintaining the network in the high capacity mode. Let Ω , Ω_D , and Ω_A be the state space, the set of direct call blocking states, and the set of alternate call blocking states, respectively:

$$\Omega = \{n : d, a \geq 0, a \leq N - r, d + a \leq N\} \quad (1)$$

$$\Omega_D = \{n : n \in \Omega, d + a = N\} \quad (2)$$

$$\Omega_A = \{n : n \in \Omega, d + a \geq N - r\} \quad (3)$$

With the symmetric and uniform traffic assumption, our analysis can be simplified to a single-link Poisson process with N servers. Fig. 2(a) shows the system state transition diagram and Fig. 2(b) shows all possible transitions and their rates for an arbitrary state (d,a) . Consider link AB at state n . Let D_n and A_n represent the direct and alternate call arrival rates on a link and let $\mu_n^{(D)}$ and $\mu_n^{(A)}$ represent the direct and alternate call departure rates. When a new call arrives and finds link AB full, alternate calls (e.g., call ABC) on that link will be randomly picked up and examined to see if rerouting can be performed so as to accommodate the new call. Let $\psi_n^{(R)}$ represents the rerouting traffic rates from a link. On the other hand, a rerouting introduces an alternate call departure on the other leg of the alternate path, i.e., link BC, as well as a direct call arriving on link AC. Let $\psi_n^{(A)}$ represents the alternate call departure rate due to rerouting and let $\psi_n^{(D)}$ represents direct call arrival rate due to rerouting. In the following sections, we will derive the state transition rates exiting from state n , i.e., $D_n, A_n, \mu_n^{(D)}, \mu_n^{(A)}, \psi_n^{(R)}, \psi_n^{(D)}$ and $\psi_n^{(A)}$, respectively. But first we will derive the blocking probability for the wavelength routed model as defined in [7].

6.2.1 Blocking in wavelength routed network:

For the wavelength routed model let B_{wR} denote the blocking probability for the end-to-end traffic. Let X_R be the random variable the number of idle wavelengths on route R . if the route consists of the single link j we may write X_j . Let $E = \{1,2,\dots,J\}$ denote the route for the end-to-end traffic. Then

$$\begin{aligned}
B_{WR} &= \sum_{m \geq 0} \Pr[X_E = 0 \mid X_1 = m_1, \dots, X_J = m_J] \times \Pr[X_1 = m_1, \dots, X_J = m_J] \\
&= \sum_{m \geq 0} p'_0(m) \prod_{j=1}^J \Pr[X_j = m_j]
\end{aligned} \tag{w1}$$

Where $m = (m_1, m_2, \dots, m_J)$. the second equality is based on $\{X_j\}$ being independent and here, again, we ignore the impact of the end-to-end traffic. We also used the notation

$$p'_n(x) = \Pr[X_R = n \mid X_1 = x_1, \dots, X_N = x_N] \tag{w2}$$

Where $R = \{1, \dots, N\}$ is any route consisting of N links, $N \geq 2$, and $x = (x_1, \dots, x_N)$, since the dimension of the vector argument may vary, p'_n denotes not a single function, but a family of functions. Nevertheless, we use the same notation and will identify the specific function involved from the dimension of the vector argument. The other term under the summation sign (w1) is obtained from the solution of the Erlang loss system:

$$\Pr[X_j = m_j] = \frac{\lambda^{C-m_j}}{(C-m_j)!} \left(\sum_{k=0}^C \frac{\lambda^k}{k!} \right)$$

The probabilities $p'_n(x)$ are computed on the assumption that the allocation of wavelengths is done randomly. The alternative is to assume that wavelengths are ordered, e.g., in order of increasing wavelength. Then, at call arrival time the wavelengths are scanned in this ordered and the first idle wavelength is allocated. While the ordered

scheme leads to smaller blocking probabilities the random case is easier to analyze and it is the one we consider in the rest of the chapter.

Let us first consider the case of a two-hop route $R = \{i, j\}$ and focus on

$$p'_n(x, y) = \Pr[X_{i,j} = n \mid X_i = x; X_j = y]$$

We can think of the x wavelengths on link i as red balls which are distributed at random in C bins, not more than one bin. The y wavelengths on link j are blue balls which are then randomly distributed in the same C bins. We calculate the probability that there are n bins which contain two balls, one red and one blue. Observe that $p'_n(x, y) = p'_n(y, x)$, by symmetry. We obtain:

$$\begin{aligned} p'_n(x, y) &= \theta(x, y, n), \quad \text{if } x \geq y \geq n, \quad x + y - n \leq C, \quad \text{and } 1 \leq x, y \leq C \\ &= \theta(y, x, n), \quad \text{if } y \geq x \geq n, \quad x + y - n \leq C, \quad \text{and } 1 \leq x, y \leq C \\ &= 0, \quad \text{otherwise.} \end{aligned}$$

Where

$$\theta(x, y, n) = \binom{y}{n} \left(\prod_{i=1}^n \frac{n-i+1}{C-i+1} \right) \left(\prod_{i=1}^{y-n} \frac{C-x-i+1}{C-n-i+1} \right)$$

6.2.2 Alternate Traffic Rate A_n

To derive A_n in terms of P_n 's, we need to obtain the intermediate system parameters λ_O , H_a , and $\beta_{a,k}$, as follows:

1) Deriving λ_O : when a new call arrives and finds the direct path blocked, the call will overflow from that link. The overflow traffic from a link with rate λ_O consists of two components. The first component represents new calls finding all channels on the direct link being occupied by direct path calls. The second component comes from new calls finding a (> 0) alternate path and $N - a$ direct path calls but the direct paths of these a calls are all full. Under this situation, these a alternate path calls cannot be rerouted to their direct paths to make room for the new calls and these new calls have to overflow onto their alternate paths. Let H_a be the probability that all the direct paths corresponding to the a alternate path calls are full. Then the overflow rate λ_O can be expressed as:

$$\begin{aligned}\lambda_O &= \lambda_D \text{Pr}[\text{direct call is blocked on the direct link}] \\ &= \lambda_D P_{N,0} + \lambda_D \sum_{a=1}^{N-r} P_{N-a,a} H_a.\end{aligned}$$

2) Deriving H_a :

Consider a tagged link carrying a alternate calls. Let $\xi_{a,k}$ be the event that the a alternate calls from k direct paths. At first sight, this is equivalent to the classical combinational problem finding the probability that k boxes are occupied when a balls

are thrown into $2M - 4$ boxes at random. But a close observation reveals that that the balls are less likely to fall into empty boxes. Let us see why. We can distinguish two types of direct paths contributing traffic to the alternate paths. The first type, denoted as ordinary direct paths, are those which do not currently have alternate path calls on the tagged link. These correspond to the empty boxes. The second type, denoted as the overflow direct paths, are those currently having alternate path calls carried on the tagged link. These correspond to the occupied boxes. It was found that these a alternate calls have some kind of *self-aggregate* property in the sense that the overflow calls are more likely to come from those overflow direct paths. Therefore, some modifications to the urn problem are needed to capture this self-aggregate effect. We start from the following recursive argument by relating the case of “ a alternate calls” to that of the “ $a - 1$ alternate calls” as follows:

$$\begin{aligned} \Pr[\xi_{a,k}] &= \Pr[\text{the additional alt. call comes from an ordinary direct path} | \xi_{a-1,k-1}] \times \Pr[\xi_{a-1,k-1}] \\ &\quad + \Pr[\text{the additional alt. call comes from an overflow direct path} | \xi_{a-1,k}] \times \Pr[\xi_{a-1,k}] \\ &= \frac{(2M - k - 3)\lambda_O / \lambda_D}{k - 1 + (2M - k - 3)\lambda_O / \lambda_D} \Pr[\xi_{a-1,k-1}] + \frac{k}{k + (2M - k - 4)\lambda_O / \lambda_D} \Pr[\xi_{a-1,k}] \end{aligned}$$

Where we assume that the overflow direct paths remain full for the additional call, and λ_O / λ_D is the probability that an ordinary direct path to chosen to join the existing set of the overflow direct paths for the additional alternate call. This equation can be solved using the initial condition $\Pr[\xi_{1,1}] = 1$ and $\Pr[\xi_{1,k}] = 0$ for $k \neq 1$.

Returning to the derivation of H_a , we have:

$$\begin{aligned}
 H_a &= \Pr[\text{all direct paths corresponding to the } a \text{ alt. path calls on the tagged link are full}] \\
 &= \sum_{k=1}^{\min(a, 2M-4)} \Pr[\text{all } k \text{ direct paths are full} | \xi_{a,k}] \times \Pr[\xi_{a,k}]
 \end{aligned}$$

Let $\beta_{a,k}$ denote the probability that a particular direct path L corresponding to one (or more) of the a alternate path calls on the tagged link is full given that there are k such direct paths. Recall that links are assumed to be statistically independent. Therefore, H_a can be further expressed as

$$H_a = \sum_{k=1}^{\min(a, 2M-4)} (\beta_{a,k})^k \Pr[\xi_{a,k}]$$

3) Deriving $\beta_{a,k}$:

To derive $\beta_{a,k}$, let us consider the rerouting of alternate calls back to the direct path L. Note that when a rerouting attempt occurs, the direct (path) link is more likely to be in a high occupancy state, as otherwise alternate routing would not take place in the first place. Therefore, the direct link occupancy as seen by a rerouting attempt is no longer P_n . Here, for simplicity, we choose to approximate it to be:

$$P_{d,a}^* = \begin{cases} P_{d,a} & d+a \in \{N-1; N\} \\ \sum_{i+j=N-1}^N P_{i,j} & \\ 0 & \text{otherwise} \end{cases}$$

By assuming the occupancy is always at either $N-1$ or N . Therefore, we have

$$\beta_{a,k} = \sum_{i+j=N} P_{i,j}^* . \text{ Note that for all cases we tried, } \sum_{i+j=N} P_{i,j}^* \text{ matches the simulation results}$$

well and also much better than the results obtained from the steady state distribution, i.e.,

$$\sum_{i+j=N} P_{i,j} \text{ (the probability of the direct link being fully occupied). In other words, } \beta_{a,k} \text{ can}$$

be better estimated through $P_{d,a}^*$'s. we are now ready to derive A_n .

4) Deriving A_n :

Consider a particular alternate path. Let the number of occupied channels on the first link be i and that on the second link be j . When the direct path is full, the LLR routing will direct the call to the alternate path with the maximum number of free circuits. When there is more than one such path, choose one at random.

Consider a particular link AC as shown in Fig. 1. If this link is full, the overflow calls of rate λ_0 will be routed randomly to one of the LLR's. Let there be a total of α such paths. Then the alternate path load of AC that falls on a particular LLR, say path ABC, is λ_0 / α .

Let Z_i be the probability that a two-link alternate path has i or more occupied circuits.

Then, with the assumptions that links are independent, we have:

$$Z_i = \sum_{m \geq 0} p'_{i,m} \prod_{j=1}^J \Pr\{X_j = m, \}$$

Given that path ABC has i occupied circuits, the probability $f(\alpha/i)$ that $\alpha - 1$ other alternate paths also have i occupied circuits each and each of the remaining $m - \alpha$ alternate paths has more than i occupied circuits is given by:

$$f(\alpha/i) = \binom{m-1}{\alpha-1} (Z_i - Z_{i+1})^{\alpha-1} Z_{i+1}^{m-\alpha}$$

Where $Z_i - Z_{i+1}$ is the probability that an alternate path has exactly i occupied circuits.

Therefore, given that path ABC has i occupied circuits, the amount of traffic y_i that gets routed from AC to alternate path ABC is:

$$y_i = \sum_{\alpha=1}^m \frac{\lambda_0}{\alpha} f(\alpha/i) = \frac{\lambda_0}{m} \frac{Z_i^m - Z_{i+1}^m}{Z_i - Z_{i+1}}$$

Given that link AB is in state $n \in \Omega/\Omega_A$, where $A \setminus B$ denotes set A minus set B, the alternate traffic rate at state n , denoted as A_n , can be obtained by removing the condition on the second link to be:

$$A_n = 2m \sum_{i \in \Omega \setminus \Omega_A} y_{\max(n^{(AB)}, i^{(BC)})} P_i$$

Where $x^{(y)}$ represents the number of calls in link y at state x .

6.2.3 Rerouting Traffic Rate $\psi_n^{(R)}$

If a new call between nodes A and B finds link AB full but has but has in it one or more alternate calls, i.e., the link is in state $(N - a, a > 0)$, then it will cause an alternate call to be rerouted to its direct path if there is a vacant channel in that direct path. In this way, the new direct call can be accommodated on link AB. This occurs with probability $1 - H_a$. Therefore, the corresponding transition rate $\psi_n^{(R)}$ from $(N - a, a)$ to $(N - a + 1, a - 1)$ is:

$$\psi_n^{(R)} = \begin{cases} \lambda_d (1 - H_a) & n \in \Omega_R \\ 0 & \text{otherwise} \end{cases}$$

where $\Omega_R \equiv \{n : n \in \Omega, a > 0, d + a = N\}$ is the set of rerouting states. As far as link AB is concerned, one direct call comes in and one alternate call departs, leaving the total number of calls unchanged.

6.2.4 Direct-Path Traffic Rate D_n

The rerouted traffic from alternate paths transforms into "extra" direct-path traffic in direct links. Assuming the alternate calls for rerouting are randomly chosen, the rerouted traffic rate ψ in a link is $\psi = \sum_{k \in \Omega_R} \lambda_d (1 - H_a) P_k$. There are two issues to note. First,

when a rerouting occurs, the distribution of trunk occupancy on the direct link seen by a rerouted call can be obtained from (8) and is given by:

$$P_{d,a}^{**} = \begin{cases} \frac{P_{d,a}}{\sum_{i+j=N-1}^N P_{i,j}} & d+a = N-1 \\ 0 & \text{otherwise} \end{cases}$$

This means that the states for which rerouting can take place are $\{(d,a) \mid d+a = N-1\}$.

Therefore, the effective rerouted traffic rate ψ' seen by these states is:

$$\psi' = \frac{\psi}{\sum_{i+j=N-1} P_{i,j}}$$

second, the extra direct traffic in a link comes from $2m$ possible links and each link contributes part of the direct traffic which is equivalent to the rerouted traffic rate of that link, i.e., ψ . But each of these $2m$ links also has $2m$ possible links for rerouted traffic to go into, or, in other words, has a probability $1/2m$ to choose the tagged link. Therefore, the extra direct traffic due to rerouting is:

$$\psi_n^{(D)} = 2m \left(\frac{1}{2m} \right) \psi' = \psi'$$

The direct-path traffic rate at state n is the sum of direct-path offered rate and extra direct traffic rate due to rerouting and is given by:

$$D_n = \begin{cases} \lambda_D + \psi_n^{(D)} & d + a = N - 1 \\ \lambda_D & 0 \leq d + a < N - 1 \\ 0 & \text{otherwise} \end{cases}$$

6.2.5 Service Rates $\mu_n^{(D)}$ and $\mu_n^{(A)}$

The rerouting of alternate calls in a link, say AB, (due to new call arrivals on that link) causes “extra” departures in another link, say BC, since an alternate call lies on a two-link alternate path. However, since link BC has $2m$ possible alternate path traffic on it and its companion link such as AB also has $2m$ possible links on which its alternate paths can possibly lie, the alternate call departure rate due to rerouting, $\psi_n^{(A)}$, is:

$$\psi_n^{(A)} = 2m \left(\frac{1}{2m} \right) \frac{\psi}{\sum_{j \neq 0} P_{i,j}} = \frac{\psi}{\sum_{j \neq 0} P_{i,j}}$$

Where $\sum P_{i,j}$ is the normalized rate of “extra” departures since rerouting only happens under the condition $a \neq 0$. The service rate $\mu_n^{(A)}$ for alternate calls at state n is increased to $\mu_n^{(A)} = a + \psi_n^{(A)}$. (19)

As a check, $\sum_{a \neq 0} (\mu_n^{(A)} - a) P_{d,a} = \psi$ as it should be. Moreover, the service rate of direct calls at state n is simply $\mu_n^{(D)} = d$.

6.2.6 System equations:

Therefore, for state $n \in \Omega$, the global balance equation is given by:

$$\begin{aligned} (\mu_n^{(D)} + \mu_n^{(A)} + D_n + A_n + \psi_n^{(R)}) P_n = & \mu_{d+1,a}^{(D)} P_{d,a-1} + \mu_{d,a+1}^{(A)} P_{d,a+1} + D_{d-1,a} P_{d-1,a} \\ & + A_{d,a-1} P_{d,a-1} + \psi_{d-1,a+1}^{(R)} P_{d-1,a+1} \end{aligned}$$

With the understanding that $P_n = 0$ for $n \notin \Omega$.

Let ρ denote the set of P_n and Λ denote the set of traffic rates $D_n, A_n, \mu_n^{(D)}, \mu_n^{(A)}, \psi_n^{(R)}, \psi_n^{(D)}$ and $\psi_n^{(A)}$. Equation (20) can be expressed as $\rho = f_1(\Lambda)$ and Λ can be expressed as $f_2(\rho)$ using the equations derived in this section. Thus, we have formulated our analysis as a fixed point model which can be solved by the successive over-relaxation (SOR) method with the set of traffic rates and probabilities obtained by f_1 and f_2 in each iteration.

Finally, with the assumption of link independence, the end-to-end call blocking probability of LLR-based rerouting is given by:

$$\begin{aligned} P_R = & \Pr[\text{direct call is blocked on the direct link}] \times \Pr[\text{all } m \text{ alternate paths are blocked}] \\ = & \lambda_o / \lambda_D \left[1 - \left(1 - \sum_{n \in \Omega_1} P_n \right)^2 \right]^m. \end{aligned}$$

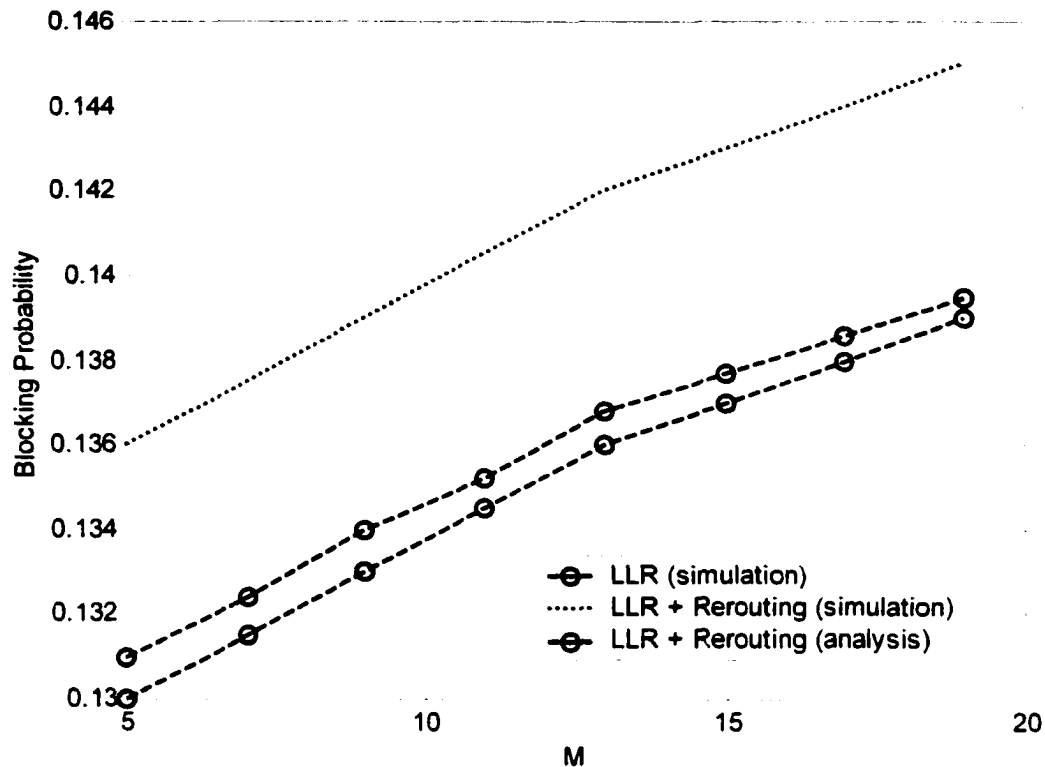


Figure 6.1 Call blocking probability against M , for $m = 4$ and $N = 20$.

6.3 Numerical results

We conduct a numerical comparison of the analytical technique against simulation results to study the accuracy of the proposed model under fully connected symmetric networks. The traffic pattern is generated using a Poisson distribution, and each connection is equally likely to be destined to any destination (uniform traffic).

Figure 6.1 shows the end-to-end call blocking P_B of LLR-based rerouting as a function of the number of network nodes M with fixed number of alternate paths $m = 4$, $\lambda_i = 19$ and $N = 20$ (number of wavelengths per link). The graph shows that the proposed analytical model is accurate, and that the approximations are valid. Figure 6.1 also shows

that a network with Rerouting achieves better overall blocking probability than a network without rerouting. And that is because; Rerouting provides better overall use of network resources, since connections are switched to optimal routes.

6.4 Conclusion

A simple rerouting scheme based on LLR was studied in this chapter. Numerical results showed that rerouting can provide a significant throughput increase over LLR. More interestingly, rerouting is shown to be an effective means of maintaining the stability of the network under dynamic routing. As using fixed-point-approximation technique, the proposed model is computationally efficient. Also, the approximation analysis is shown to be quite accurate.

Chapter 7

7. Conclusion

This dissertation makes five important contributions to the body of knowledge in the design and analysis of scalable, reliable, and cost-effective traffic engineering components for next-generation WDM optical networks. The ideas and techniques developed in this dissertation can be utilized in designing and implementing next-generation WDM optical networks. This chapter summarizes the main results and contributions in this dissertation.

7.1 Real Time Provisioning in IP over WDM Optical network

This chapter has considered the problem of real-time provisioning of optical channels in a hybrid IP-centric WDM-based networking model. Provisioning implies that an optical channel is successfully routed if both an active path (working) and another alternate link-disjoint path (backup) are set up at the same time. Specifically, the work presented here has addressed the implementation issues of the path selection component of the traffic-engineering problem in such a network. Methodologies and associated algorithms for dynamic lightpath computation were outlined.

We have presented and compared the performance of two different constraint-based routing and wavelength assignment (RWA) algorithms, for dynamic provisioning of the optical channels. Specifically, the RWA scheme is used to compute end-to-end dedicated and shared backup paths to protect against single link/node failures. Three path selection schemes have also been proposed for each algorithm. Both algorithms are based on a fully distributed implementation. The performance of both algorithms is then compared with that of the conventional static RWA algorithm. It is shown that the dynamic full-adaptive algorithm outperforms the semi-adaptive one, and both of them significantly outperform the conventional static algorithm. It's also shown that the Future Cost-Based Selection scheme outperforms both the total-based and the balanced selection schemes.

7.2 Impact of Wavelength Converters on the Performance of Optical Networks

This work presented a quantitative analysis on the benefit of wavelength conversion in DWDM networks with limited number of wavelength converters assuming a novel traffic model that has not used before. Specifically, we have assumed a traffic model that represents a more practical situation, namely, that of transporting OC-48 (and OC-192 or higher) "private line" traffic. This traffic is characterized by very long holding time (typically in months) and tends not to be rearranged, since connection path rearrangements often cause traffic "hits" (short time failures). Novel switch architecture with partial wavelength conversion capability has also been considered. For the network topology and traffic pattern considered, the simulation results have indicated that the

performance of an optical network with only 25% of wavelength conversion capability is very close to that of an optical network with full wavelength conversion. In another Metro application, we observe that the use of wavelength converters does not have any impact on the network performance.

7.3 Connection Management for Wavelength-Routed WDM Networks

This chapter has proposed two new distributed signaling protocols for fast automatic setup and tear-down of paths across the emerging interconnection models for IP-over-optical- networks. The first scheme is probe flooding-based routing (PFBR) algorithm with backward reservation while the second scheme is based on an adaptive routing algorithm called *Multi-Path Routing (MPR)* where k paths are probed simultaneously. Time discrete simulation tool has been developed to examine the effectiveness of the proposed algorithms in terms of call acceptance rate (CAR), call set-up time (CST), average routing distance (ARD), and bandwidth required for control messages. The simulation results have revealed that the proposed PFBR algorithm is superior in terms of CAR at the cost of ARD, CST, and bandwidth requirements for control messages, whereas the MPR-FCFS offers the lowest CST and ARD at the expense of CAR.

Also this work has investigated and compared the performance of two GMPLS-based distributed control and management protocols for dynamic lightpath provisioning in future IP networks. The first protocol is a global information-based link state approach that consists of both an integrated RWA algorithm and a signaling algorithm. Two

triggering mechanisms for the LSAs update procedures are considered; one is periodically-based and the other is threshold-based update. The second protocol is a local-information based fixed alternate link routing approach where the signaling protocol is closely integrated with the RWA protocols. The performance of the two protocols is compared in terms of three metrics, namely, (a) connection setup time, (b) blocking probability, and (c) bandwidth requirements for control messages. It is shown that the global information-based link state approach with both its LSAs triggering mechanisms outperforms the local information-based fixed alternate link routing approach in terms of blocking probability and connection setup time; but it requires more signaling overhead. It has also been shown that threshold update triggering mechanism outperforms the periodical update triggering mechanism in term of connection setup time. Furthermore, it requires significantly less control signal overhead.

7.4 Distributed Connection Management Protocols for Survivable WDM Optical Networks

In this chapter, we proposed an on-line control and management protocol for fast lightpaths provisioning and restoration. The proposed management protocol has RWA, signaling, link state update, fault detection and recovery, and rerouting capabilities. A new "Token-Based" distributed rerouting algorithm is proposed. Under our current assumptions of message processing speed and switch configuration time, the connection-recovery time in the NSFNET network (figure 1) when applying link-based, path-based, or path-based plus rerouting restoration schemes is under 50 ms. That is an acceptable

recovery time. Also the simulation results show that the proposed rerouting algorithm improve the network throughput and reduce the overall blocking-probability.

7.5 Analysis of rerouting in Wavelength-Routed WDM Networks

A simple rerouting scheme based on LLR was studied in this chapter. Numerical results showed that rerouting can provide a significant throughput increase over LLR. More interestingly, rerouting is shown to be an effective means of maintaining the stability of the network under dynamic routing. As using fixed-point-approximation technique, the proposed model is computationally efficient. Also, the approximation analysis is shown to be quite accurate.

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