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Multiwavelength Optical Networks Capabilities for Next Generation Internet

by

Yinghua Ye

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

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ABSTRACT

MULTIWAVELENGTH OPTICAL NETWORKS CAPABILITIES FOR NEXT GENERATION INTERNET

by

Yinghua Ye

Adviser: Professor Mohamed A. Ali

This thesis addresses the important problem of how to bridge the gap between Dense-Wavelength Division Multiplexed (DWDM) optical networks and Next-Generation Internet (NGI) and examines, at both the physical layer and the higher layers protocol, how the capabilities of DWDM technology can be used: 1) To support the explosive traffic demands of NGI, and 2) To take DWDM from a mere fiber multiplication method to its new phase of becoming the world's intelligent bandwidth infrastructure.

To meet this explosive demand, this work presents a novel, dynamic, survivable, and scalable ultra-high speed DWDM-based Self-Healing Ring (SHR) network topology capable of supporting an aggregate network capacity in the order of a Tb/s per fiber.

Specifically, this thesis examines, through computer simulation and modeling, the technological requirements and assesses the performance analysis and feasibility for implementing such network fabric based on SHR network topology and DWDM technology. To ensure that the network is scalable, a network planning and optimization strategy, at the initial phase of the system design, will also be developed.

The second main issue that this thesis will address is how to move DWDM from a mere "dumb" fiber multiplier technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer. This thesis investigates two different options for the implementation of one of the most critical networking functionality associated with ultra high capacity transport networks, namely "Network Survivability". The first option assumes that the full protection/restoration functionality can be implemented at the optical layer. We present a novel mesh-based hybrid optical protection scheme that utilizes multifiber physical links along with hierarchical OXC structure. The second option assumes that protection/restoration functionality can be allocated between the optical layer and the data layer.

This thesis examines the notion of supporting "data directly over optics". This work combines recent advances in multiprotocol label switching (MPLS) traffic engineering control plane constructs with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks. Finally, we

present and develop a simple and integrated hybrid protection/restoration scheme that can be coordinated at both the IP and WDM layers.

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Much appreciation is given to Dr. Gengxian Luo, who is the first one that introduced me to optical communication field, and gave me wonderful advice in my life. I thank my friends Xiaoling Huang, Liyun Wang, Chadi Assi, and Abdallah Shami for their kindly help and encouragement throughout my study.

Finally, I dedicate my work to my parents, and sisters. I am very proud of being in such a wonderful family. I believe they are all happy to see me accomplish my goal.

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CHAPTER 1

INTRODUCTION

1-1. Introduction

Over the past few years, the field of computer and telecommunications networking has experienced tremendous growth. Traffic demand has increased substantially, somewhat unexpectedly, prompting carriers to add capacity quickly and in the most cost-effective way possible. This growth is driven by private networks (Intranets), as well as the public Internet. The growth of the capacity of public Internet backbones is driven in large part by the popularity of the World Wide Web. Internet backbone capacity is doubling every three to four months, resulting in a factor of 10 increase annually. The change in the fundamental character of backbone network traffic will change the type of network equipment that supports the backbone in the future. As more users start to use the Internet, and as their usage patterns evolve to include more bandwidth-intensive networking applications, there emerges an acute need for ultra-high capacity backbone transport network facilities whose capabilities greatly exceed those of current high-speed networks. There is no sign that this increase is an anomaly, and both traffic and backbone capacity are likely to continue a rapid increase into the foreseeable future.

The key to upgrading current high-speed transport networks rests in the relatively young field of fiber optics. Given that fiber has a potential bandwidth of approximately

50 Tb/sec, nearly four order of magnitude higher than peak electronic data rates, every effort should be made to tap into the capabilities of fiber-optic networks. One technique for accessing the huge bandwidth available in an optical fiber is wavelength-division multiplexing (WDM). In WDM, the optical transmission spectrum is divided into a number of nonoverlapping wavelength bands, with each wavelength supporting a single communication channel operating at peak electronic speed. Multiple numbers of these channels can then be transported through a single fiber, thus tapping into the huge fiber bandwidth. The challenge is to design and develop appropriate network architectures, components, protocols, and algorithms to support such a system.

A WDM system is constituted of several key elements such as: WDM terminals (transmitters and receivers), WDM repeaters, e.g., Erbium-doped fiber amplifiers (EDFAs), and WDM filters. Optical amplifiers can simultaneously accommodate multiple optical channels and therefore have greatly accelerated the pace at which WDM systems are being developed and deployed. Important to the effectiveness of this system are high performance transmitters and receivers. Many challenges are encountered in the design of these devices to ensure high quality transmission in WDM systems. In addition, low loss, high resolution WDM filters are also crucial for WDM communication systems.

The two protocols which will dominate the backbone in the future are IP, the Internet Protocol, and ATM, Asynchronous Transfer Mode. While there is much speculation about which of these two protocols will dominate, it is likely that both will be important, and fill complimentary roles. What types of transport systems can best interconnect a network of IP routers and ATM switches with port speeds of 2.5-10 Gb/sec? Dense-Wavelength division Multiplexing (DWDM) technology has emerged as the transport technology of choice for the long-haul transmission systems and has already successfully penetrated the long-haul telephony infrastructure. Communication system suppliers are advertising DWDM transmission systems with capacities greater than 500 Gb/sec over a single fiber by means of multiplexing more than fifty channels at 10 Gb/sec each. Much of this capacity growth has been in point-to-point long-distance backbone transmission. DWDM technology is expected to dominate the backbone of the Next-generation Internet (NGI) and is poised to play a greater role in the access environment. A ring topology has been selected as a powerful candidate for introducing DWDM into the access environment due to the inherent reliability of a ring. In addition, a mesh-based backbone transport network topology can be partitioned into several smaller inter-connected rings. Thus, a ring topology will constitute the fundamental building block for the NGI backbone transport network facilities.

What is needed is a dynamic and survivable DWDM-based ultra-high speed Self-Healing Ring (SHR) network topology, that is the focus of this thesis, that has the capabilities to scale sufficiently in capacity to meet the exponential growth in bandwidth demand as well as to provide an effective and robust networking solution. This network must be capable of supporting up to 100 channels (wavelengths) at 2.5-10 Gb/sec per channel for an aggregate network capacity in the order of a Tb/sec per fiber.

The implementation of such high capacity DWDM-based core transport networks, although providing great economic advantages through multiplexing and sharing of transport facilities, increases the vulnerability of telecommunication services using these transport facilities. Consequently, "Network Survivability", which is the ability of network to recover traffic affected by failures, becomes a key consideration in the design of such high capacity DWDM-based core transport. Early deployment of DWDM technology has mainly been in a point-to-point manner to increase link bandwidth, supports little in terms of networking functionality and do not yet perform traffic protection or restoration. In cases of fiber cuts or network failures, SONET/SDH equipment would usually provide these functions, with WDM used strictly for fiber capacity expansion. However, recent advances in WDM components and subsystems (WDM add/drop multiplexers (WDM-ADM), optical cross-connects (OXCs)), 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 DWDM technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer.

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 is too slow to scale, which make it ineffective as the architecture for the envisioned next generation optical data networks. An important and challenging consideration in such multi-layer transport networks is the inter-working of optical survivable architectures with existing similar survivability schemes that are already available at the higher layers. The major challenges are to determine which layer(s) is responsible for each failure (recovery approach), to establish a strategy to coordinate single-layer recovery actions (escalation strategy). These strategies are critical to the integration of WDM technology into telecommunications networks.

Providing survivability at the optical layer, that is the second focus of this thesis, is inherently attractive, but whether it makes practical sense, given similar mechanisms that are already available at the higher layers (e.g., SONET/SDH, ATM, IP) poses serious challenges and raises many questions. This thesis will attempt to address these issues. To address the limitations of the multi-layering approach and expedite multi-vendor interoperability, a more direct IP standards-based approach for closer and efficient IP-WDM integration is needed. If IP can be mapped directly onto the WDM layer, some of the unnecessary network layers can be eliminated, opening up new possibilities, as this work will show, for developing a simple and integrated hybrid protection/restoration scheme that can be coordinated at both the IP and WDM layers.

1-2. Thesis Statement

This thesis addresses the important problem of how to bridge the gap between DWDM optical networks and the Next-Generation Internet and examines, at both the physical layer and the higher layers protocol, how the capabilities of DWDM technology can be used: 1) To support the explosive traffic demands of the Next Generation Internet, and 2) To take DWDM from a mere fiber multiplication method to its new phase of becoming the world's intelligent bandwidth infrastructure, that is to evolve DWDM technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer.

Aggregate bandwidth required by the Internet in the US by the year 2005 is expected to be in excess of 35 Terabytes/sec. To meet this anticipated need (achieve the first objective), this work presents a novel, dynamic, survivable, and scalable ultra-high speed DWDM-based SHR network topology capable of supporting up to 100 channels (wavelengths) at 2.5-10 Gb/sec per channel for an aggregate network capacity in the order of a Tb/sec per fiber. Specifically, this thesis examines, through computer simulation and modeling, the technological requirements and assesses the performance analysis and feasibility for implementing a dynamic and scalable ultra-high speed transport network fabric based on SHR network topology and DWDM technology.[1,4-5] A ring topology has been selected here for two main reasons: 1) It is considered as a powerful candidate for introducing DWDM into the access environment due to its inherent reliability, and 2) A mesh-based backbone transport network topology can be partitioned into several smaller inter-connected rings. Thus, a ring topology will constitute the fundamental building block for NGI backbone transport network facilities. To ensure that the network is scalable, a network planning and optimization strategy, at the initial phase of the system design, that allows a smooth network evolution while maintaining adequate end-to-end performance, independent of the network size, for all wavelength signals across the network will also be developed.

The second main issue that this thesis will address is how to move DWDM from a mere "dumb" fiber multiplier technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer. A key issue in implementing this approach in a DWDM-based data centric network is to avoid the wasteful duplication of functionality at both the optical layer and the higher layers (data layers). This thesis investigates two different options for the implementation of one of the most critical networking functionality associated with ultra high capacity transport networks, namely "Network Survivability". The first option assumes that the full protection/restoration functionality can be implemented at the optical layer. In view of this option, we investigate the potential and limitations of providing full protection/restoration functionality at the optical layer, and whether it makes practical sense, given similar mechanisms that are already available at the higher layers (e.g., SONET/SDH, ATM, IP). Specifically, we present a novel mesh-based hybrid optical protection scheme that utilizes multifiber physical links along with hierarchical OXC structure, which is a combination of fiber cross-connects (FXCs) and wavelength selective cross-connects (WSXC's).

The second option assumes that protection/restoration functionality can be allocated between the optical layer and the data layers. A central issue for the successful implementation of this option is the reduction of the cost and complexity associated with today's multi-layer core transport network architecture. This may be achieved through the elimination of unnecessary network layers, to avoid functional overlap and wasteful duplication, among today's conventional four-layers core transport network model. In this view of reduced or "collapsed" network layers, this thesis examines the notion of supporting "data directly over optics", where existing TDM systems (e.g., SONET/SDH) play a diminishing role, and Optical Transport Networking emerges as the underlying transport infrastructure for the envisioned "DWDM-based IP-centric optical Internet". To address the limitations of the multi-layering approach, this work presents an overview of a more direct IP standards-based approach for closer and efficient IP-WDM integration. This approach combines recent advances in IP multiprotocol label switching (MPLS) traffic engineering control plane constructs[6-9] with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks. Finally, having established the notion of mapping IP directly onto the WDM layer, we present and develop a simple and integrated hybrid protection/restoration scheme that can be coordinated at both the IP and WDM layers.[2-3]

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CHAPTER 2

NETWORK SCALABILITY

2-1. Introduction

Aggregate bandwidth required by the Internet in the US by the year 2005 is expected to be in excess of 35 Terabytes/sec. To meet this anticipated need, a survivable, and scalable ultra-high speed core transport network capable of supporting for an aggregate network capacity in the order of a Tb/sec is required. One of the major issues that has to be carefully considered, when upgrading current transport network capacity is network scalability. Network scalability refers to how can one scale up the size and capacity of the network, to accommodate gradual/sudden increase in traffic demand without affecting/changing the existing networking infrastructure. To ensure that the network is scalable, a network planning and optimization strategy, at the initial phase of the system design, that allows a smooth network evolution while maintaining adequate end-to-end performance, independent of the network size, for all wavelength signals across the network will be developed in this chapter.[1] We select a ring topology as a candidate to investigate the scalability and survivability issues of core transport network.

2-2. Overview of Self-healing Ring Network

A bi-directional WDM SHR architecture is appropriate for connecting a set of broadband switches with full mesh traffic pattern. Figure 2-1 illustrates the block diagram of such WDM SHR.[2,5-8] The protection is at optical layer by two optical switches in each direction.

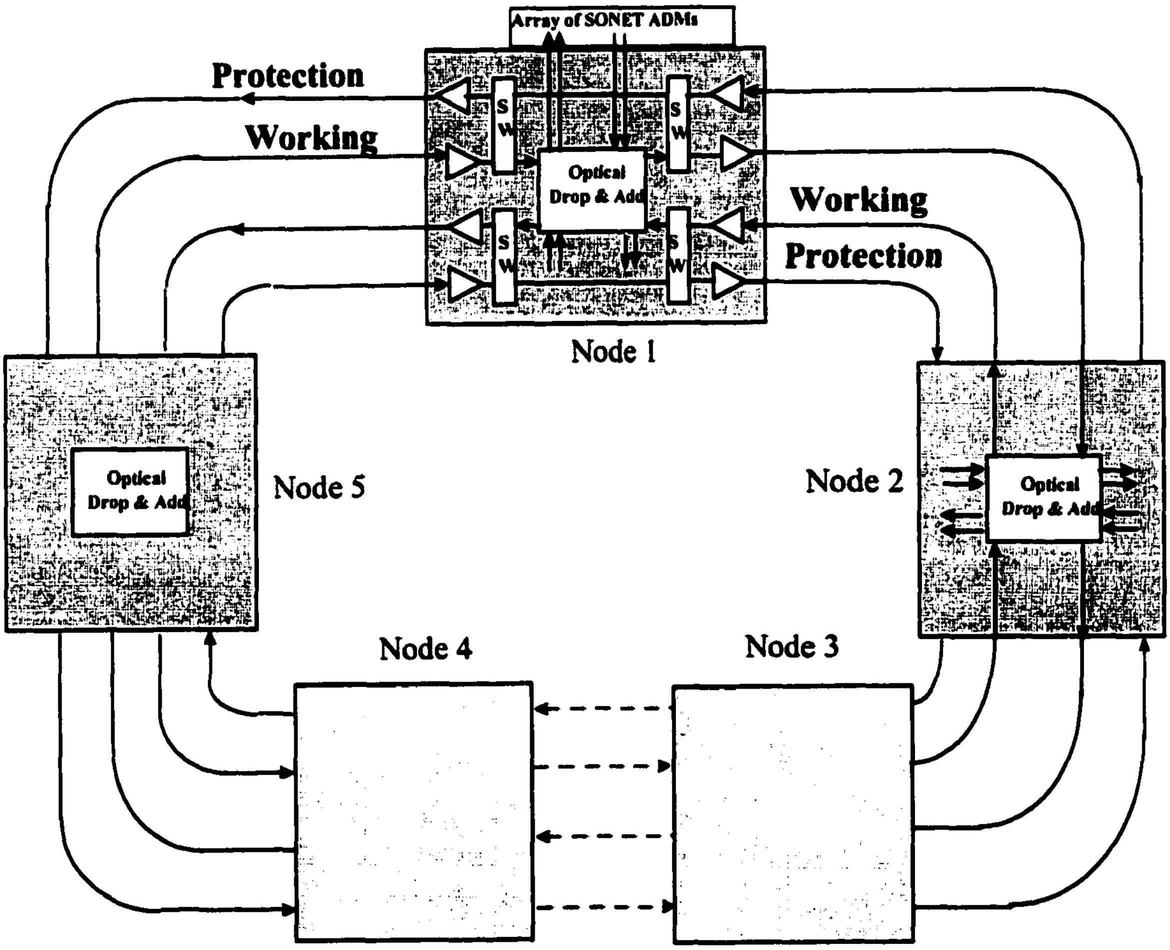
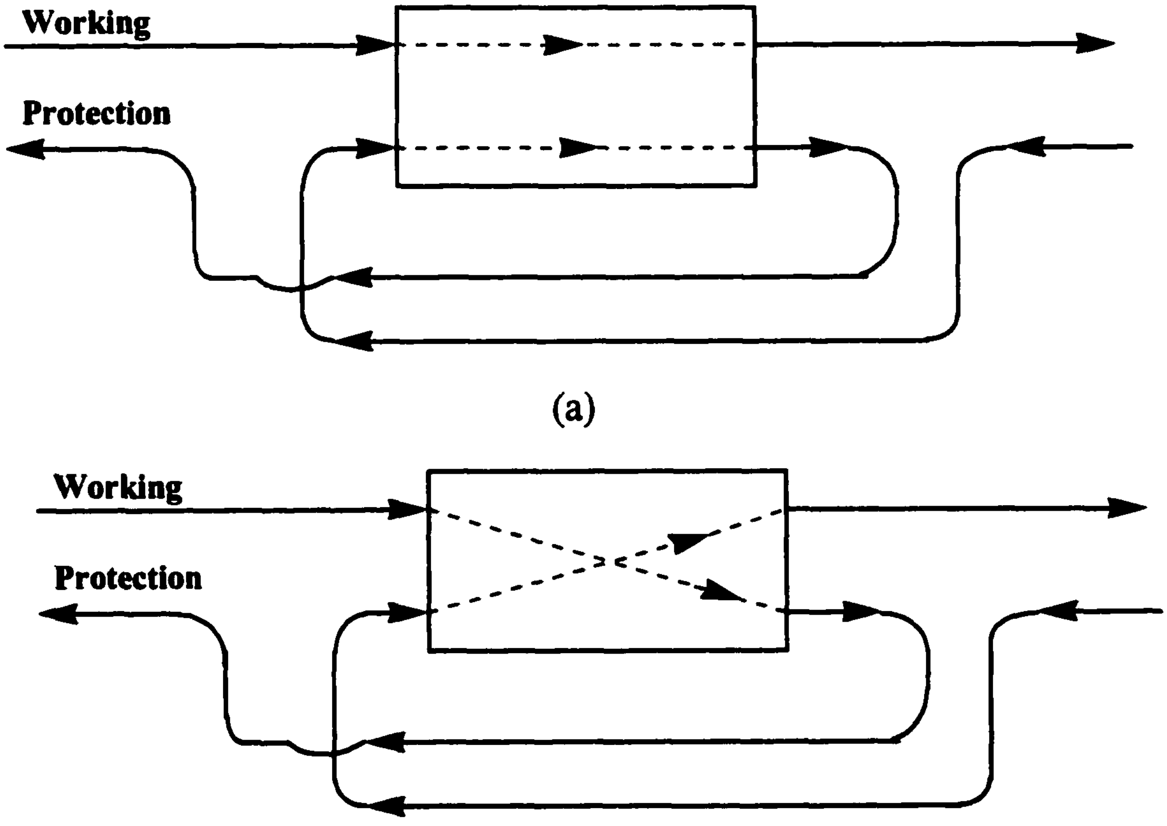


Figure 2-1. 4-fiber bi-directional self-healing WDM ring

The optical switches used here are the 2x2 non-blocking switches, which are shown in Figure 2-2. Figure 2-2(a) shows the protection switch in failure free status. Figure 2-2 (b) illustrates when the failure occurs, the optical switch cross-connects the traffic from working fiber to the protection fiber in different route. The switching time is 15 ms for Latching style and 20 ms for Non-Latching style.[8]



(a)

(b)

Figure 2-2: 2x2 non-blocking optical switch, (a) by pass status, (b) switching status

This configuration can protect both link failure and optical equipment and SONET ADM failure in the optical layer. The block diagram of the network under a line failure between node 1 and node 2 is shown in Figure 2-3. The optical switches at both sides of the link are reconfigured in a way that allows the traffic from node 1 to node 2 go through node 5, node 4, node 3 and finally node 2 on the protection path. The block diagram of protection state of equipment failure inside the optical node is shown in Figure 2-3. In this case, all optical switches at both sides of the node are reconfigured to allow continuous communications between the all other nodes and isolate the failure node. The protection switching decision is made at optical layer. Therefore, the SONET ADMs can be much simpler than the conventional BLSR.

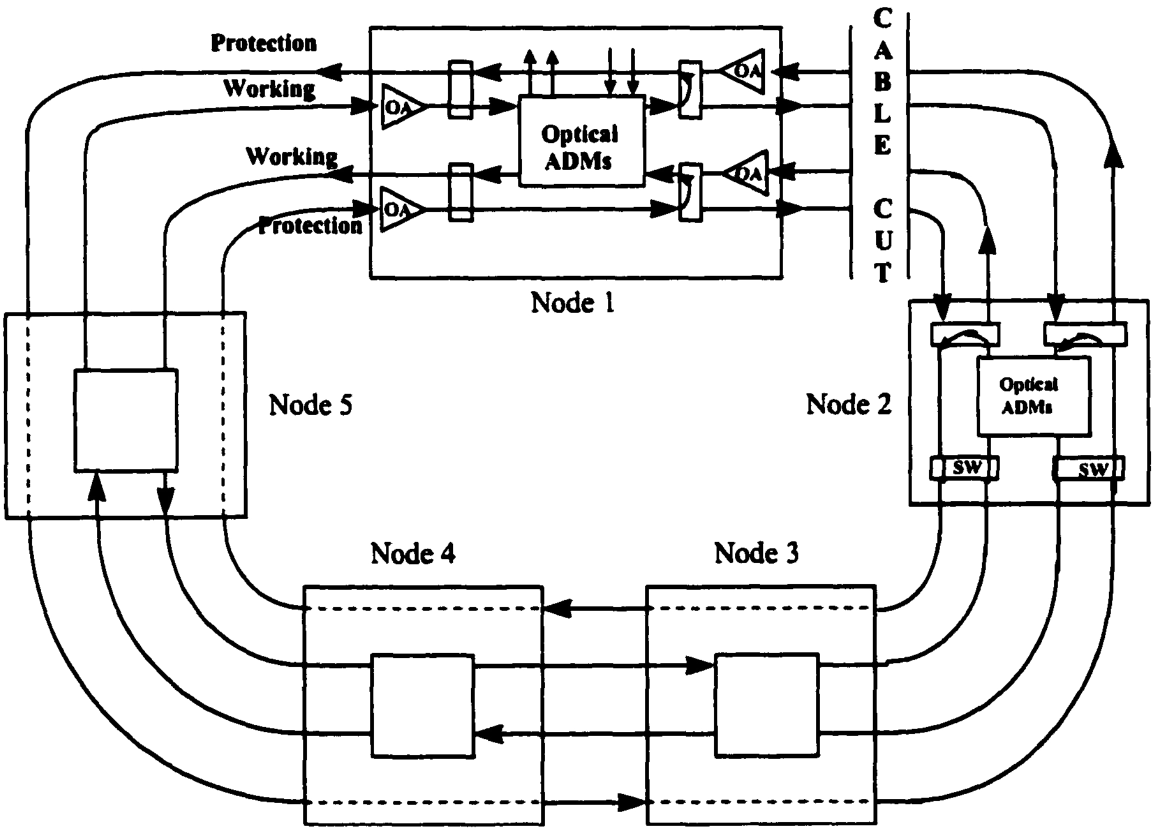


Figure 2-3. Block diagram of protection state at fiber cut between Node1 and 2

The advantages of using all-optical protection are that: (1) the network can achieve the transparency at bit rate and format, (2) the network architecture will be simpler. But the optical protection only can protect facility failure. When the equipment failure happens, like in Figure 2-4, the optical protection can only isolate this failure equipment out and keep the rest of the network working.

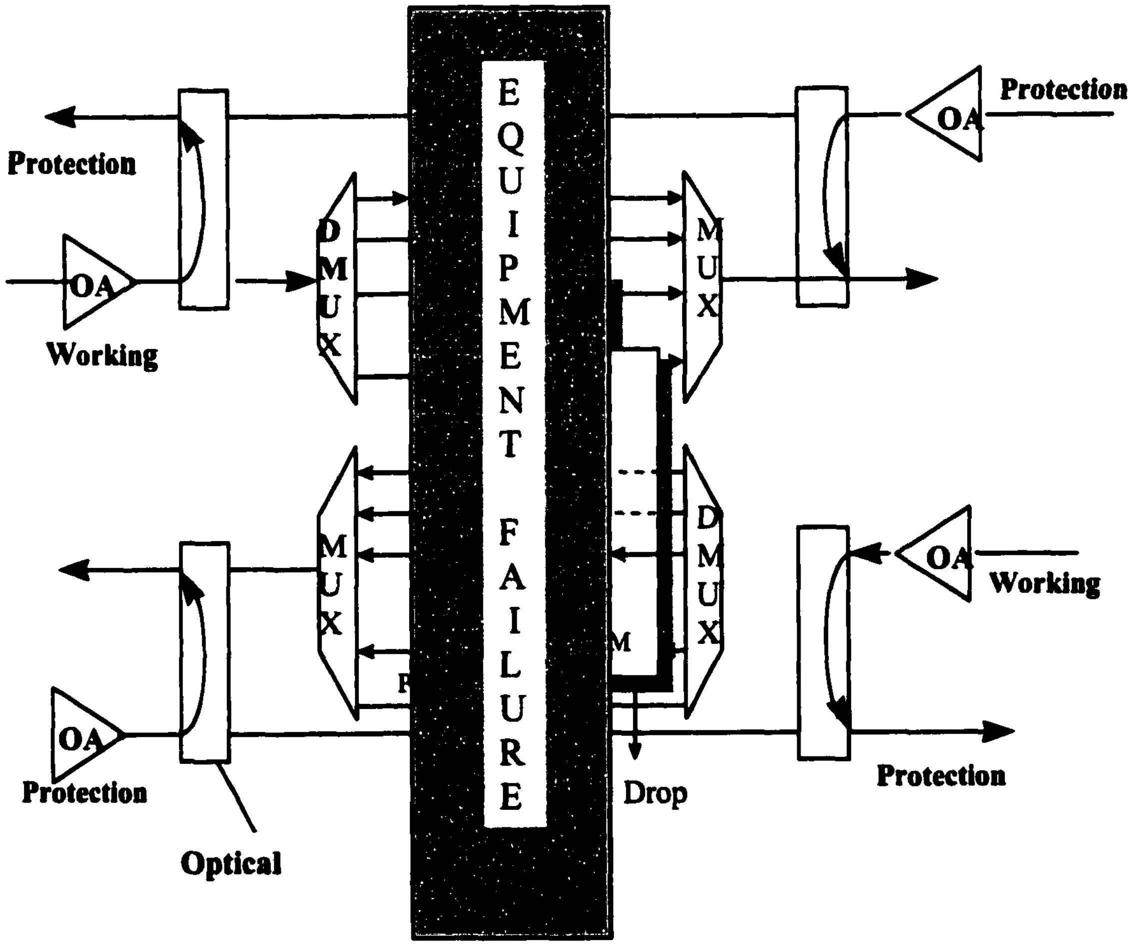


Figure 2-4. Block diagram of protection state at equipment failure

2-3. Optimal Wavelength Planning and Performance Analysis for Scaling DWDM-based Core Transport Network

2-3-1. DWDM-based Core Transport Network Evolution

While WDM is expected to dominate the backbone, its role in an access environment is just beginning to take shape, with vendors starting to discuss WDM access network solutions, particularly to serve business customers. Huge bandwidth is one advantage of deploying WDM in an access environment; however, the main advantages lie in the enhanced flexibility and upgradability that WDM provides.

Because of the proximity of the end-users, an access network is quite different from a from a long distance backbone network. A backbone network carries traffic that, for the most part, has already been multiplexed and groomed, and hence has less variability. On the other hand, the traffic characteristics of an access network is highly variable subject to the ever increasingly customer demand. An access network must accommodate a wide range of data formats and data rates. In addition, it must also be scalable in terms of both number of customers and traffic demands of any given customer. Thus, an access network needs to be more flexible and scalable. WDM ring network is capable of providing restoration capabilities and can be a powerful candidate for both backbone and access network application. Figure 2-5 shows a high-level view of an access network architecture that is functionally partitioned into the multiple distribution networks and the feeder network.[2] End users are locally connected to the distribution networks, which in turn are connected to the access nodes in the feeder network. In addition to connecting access/egress nodes to one another, the feeder network also has one or more connections to the communication backbone via the egress nodes. The feeder network has a ring topology on which are located a set of access nodes and egress nodes. Feeder access nodes can be interconnected by multiple fibers for greater capacity and route diversity. We use 4-fiber bi-directional WDM ring network feeder configuration for its simplicity while providing powerful protection function in case of fiber cuts.

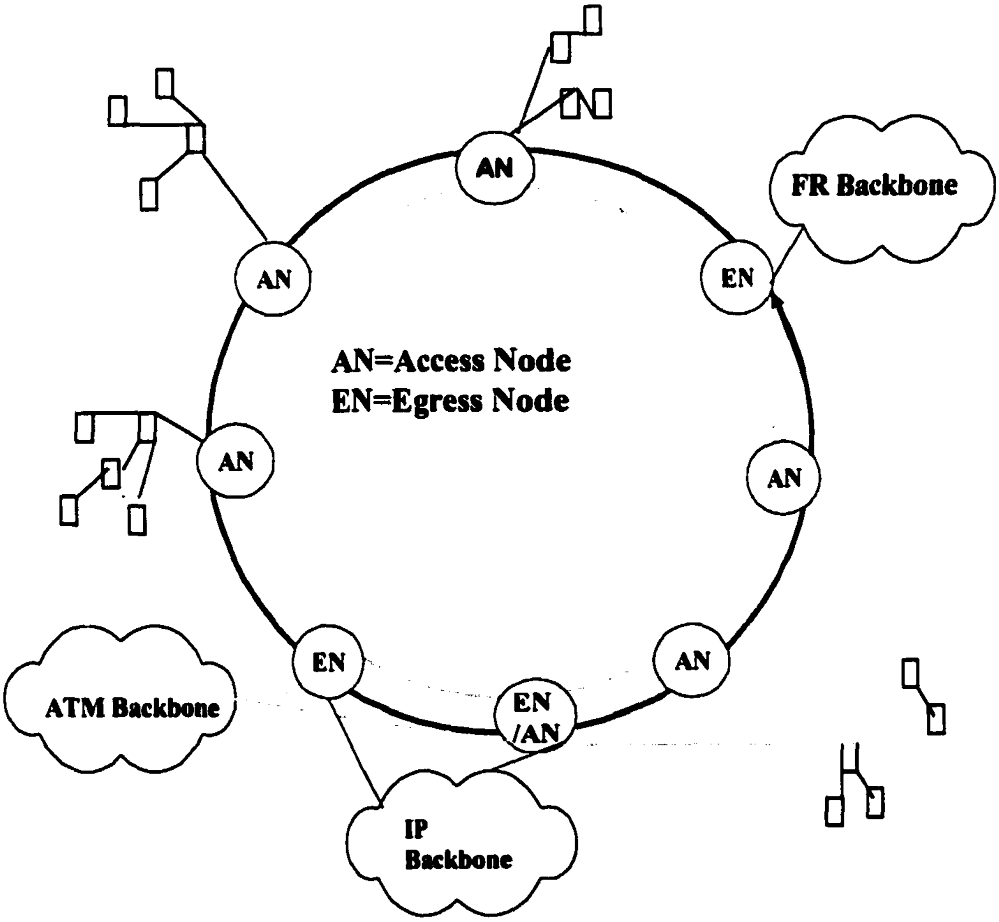


Figure 2-5. The high-end access network architecture

As the number of end-users increase, and as their usage patterns evolve to include more bandwidth-intensive internet applications, there emerges an acute need to scale up the number of the nodes of the feeder ring network while satisfying the following two critical requirements:

1. The wavelength assignment plan should provide a full-mesh traffic pattern among all nodes while allowing a graceful network evolution scenario from a standard single wavelength small SONET (3-node) ring to a multiwavelength full-mesh connected large ring with N nodes (N > 3) with the following criterion: the addition of every new node will not change the wavelength assignment for the nodes already in the network.

2. Maintaining adequate end-to-end performance for all wavelength signals across the ring should be independent of the network size and/or the total span length traversed by a given signal wavelength. As the network size scales up, a given signal wavelength would now traverse more nodes en route to its final destination in order to keep the same connectivity. Signal degradation can occur at each node due to finite filter passband and filter misalignment, added crosstalk signals, added Erbium-doped Fiber Amplifier ASE noise, and wavelength dependent gain.

Therefore, a network planning and optimization strategy that allows a smooth network evolution while maintaining adequate end-to-end performance, independent of the network size, for all wavelength signals across the ring is needed at the initial phase of the system design. We show here that satisfying only the first requirement may not be sufficient to achieve adequate end-to-end performance for all wavelength signals across the ring.

The next section presents a scalability performance analysis of a full-mesh WDM ring network when operated in an access environment. Specifically, we propose a novel and simple Networking Planning and Optimization Tool (NPOT) that interrelate the networking layer wavelength assignment algorithm with the physical layer transmission impairments for best overall full-meshed connected WDM ring performance when operated in an access environment.

2-3-2. Network Planning and Optimization Tool (NPOT)

As an illustrative example, we consider a 4-fiber bi-directional WDM ring topology as the feeder network for an access environment. We start up with 3 nodes and then scale up this number up to 15 nodes (2 nodes are assumed to be added at each stage). Figure 2-7 shows one of the extreme cases of the network evolution from 3-nodes single wavelength ring up to 15-nodes 28 wavelengths mesh connected ring (the number of the node indicates the sequence of the node being added on). The entire sequence of adding the nodes is shown in Figure 2-7, and a connectivity and wavelength assignment algorithm for the network evolution is determined (according to the above first requirement) based on the following described approach.

A matrix approach has been found to work best for wavelength assignment algorithm for 4-fiber SHR. By appropriately filling in the matrix, while following some simple rules, we can get all the wavelength assignment. Figure 2-6 (I) shows an example of a matrix for a ring network with N=5 nodes (3 wavelengths required). The value placed in the matrix represent half of the connections (clockwise direction only) from each node to every other node on the ring. A value *K* in position (i, j) states that node j is connected to node *(j+K) mod (N)* using wavelength i. Figure 2-6 (II) shows the full mesh connectivity for this ring and the wavelength assignment obtained from the matrix for the clockwise direction connections. The identical assignment is valid for the rest of connections in the counter-clockwise direction.

(I)

	A	B	C	D	E
W1	1	2	X	2	X
W2	2	X	1	1	1
W3	X	1	2	X	2

(II)

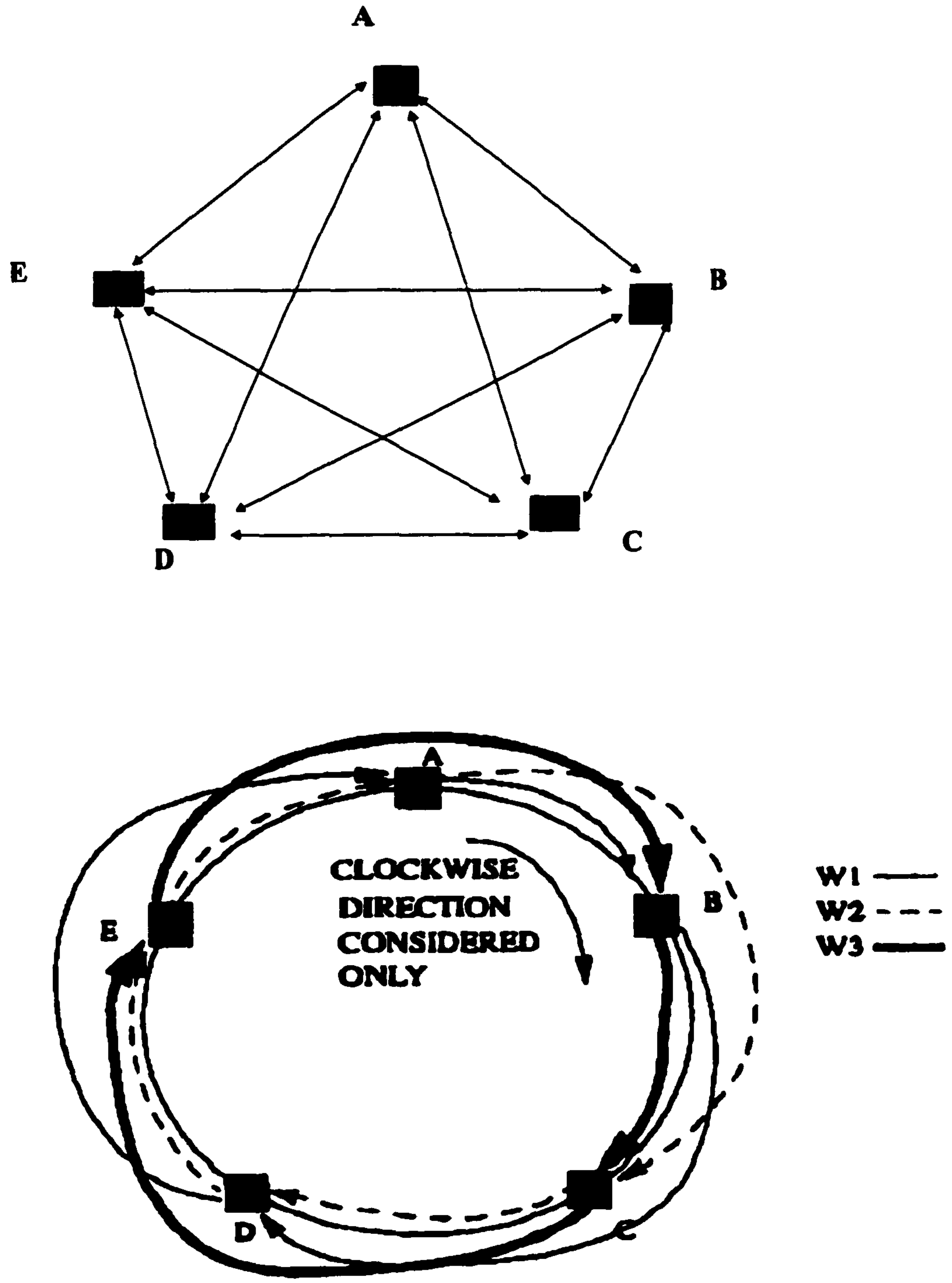


Figure 2-6 (I) Wavelength assignment matrix for N=5 nodes on the ring, (II) Wavelength assignment for a ring with N=5 nodes

The general rules for the wavelength assignment algorithm are:

1. K is the number of node for one wavelength cross over including the originating node. The maximum number is (N-1)/2.

2. In a row (wavelength), wherever put the number K in the matrix, one must leave K-1 spaces blocked not available for any number. If one does not block these spaces on that row, someone else uses the same wavelength on the same segments which cause two paths intersect.
3. In a column, one can not have two K values the same. Otherwise one would have duplicated path using different wavelength.

4. Summation of all the values in a row must equal to N. This is true because one wavelength has to go over the close the ring exactly once.

5. When follow the rules above, the summation of one column should equal to total number of wavelength.

Network evolution requires scaling the existing network by adding a single node at a time, without disrupting already existing connections, this matrix filling method is extended to satisfy this requirement according to the different characteristics of scaling rings with even and odd number of nodes.

<u>Case 1</u>: the network extends from even number of node ($N_{new}=N_{odd}+1$)

The matrix size for existing ring network is W X N ($W=\frac{N^2-1}{8}$) to W' X N_{new}, here $W'=\frac{(N_{new})^2}{8}$ or $W'=\frac{(N_{new})^2+4}{8}$. The new column can be added at any position in the matrix. For each row, from the new column, the algorithm traverses the row towards the left until it encounters the first entry (other than X). The first W rows of the new column are then filled following rules 1 and 2 below. The rest of the rows are filled with the longest connection entries.

Rule 1: If the entry encountered, K, is not an entry of a longest connection L_{max}, ($L_{max}=\left\lfloor\frac{N_{odd}}{2}\right\rfloor$), place an X at the new column and increment K by 1.

Rule 2: If the entry encountered K, equals to L_{max}, the algorithm places the number M=Q+1 at the new column and entry K becomes K'=(K-Q). The number of Q denotes the number of X's that follow the new column for the specific row.

<u>Case 2</u>: the network extends from odd number of node ($N_{new}=N_{even}+1$)

The matrix is expanded from W X N_{even} to $W'\times N_{new}$ ($W'=\frac{(N_{new})^2-1}{8}$). For the new column, for rows 1,...,($\frac{(N_{even}-1)^2-1}{8}$), the algorithm follows Rule 1. For rows

$\frac{(N_{even}-1)^2-1}{8}+1,\ldots,$ W (where W equals to the number of wavelengths for N_{even} ($W=\frac{N_{even}^2}{8}$) if N_{even} is divisible by 2 and 4 or $W=\frac{N_{even}^2+4}{8}$ if N_{even} is divisible by 2 but not by 4, the algorithm follows Rule 2. For rows (W+1), ..., W', the algorithm places in the new column the connection entries that are not used in the rows above for that column. The rest of the row entries are filled appropriately. Table 2-1 shows the routing and wavelength assignment for 15 nodes on the ring, which evolves from 3 nodes ring.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W1	7	X	X	X	X	X	X	1	7	X	X	X	X	X	X
W2	X	X	6	X	X	X	X	X	1	1	1	2	X	4	X
W3	4	X	X	X	5	X	X	X	X	2	X	1	1	2	X
W4	6	X	X	X	X	X	2	X	2	X	2	X	3	X	X
W5	2	X	4	X	X	X	4	X	X	X	3	X	X	1	1
W6	X	X	X	X	4	X	X	X	3	X	X	3	X	X	5
W7	X	X	7	X	X	X	X	X	X	3	X	X	2	X	3
W8	1	1	2	X	7	X	X	X	X	X	X	4	X	X	X
W9	X	7	X	X	X	X	X	X	4	X	X	X	4	X	X
W10	X	5	X	X	X	X	3	X	X	4	X	X	X	3	X
W11	X	3	X	X	6	X	X	X	X	X	4	X	X	X	2
W12	X	X	1	1	2	X	6	X	X	X	X	X	5	X	X
W13	X	X	X	5	X	X	X	X	5	X	X	X	X	5	X
W14	X	X	X	6	X	X	X	X	X	5	X	X	X	X	4
W15	3	X	X	7	X	X	X	X	X	X	5	X	X	X	X
W16	X	2	X	3	X	X	5	X	X	X	X	5	X	X	X
W17	X	X	X	X	1	1	7	X	X	X	X	X	X	6	X
W18	X	X	X	X	X	3	X	X	6	X	X	X	X	X	6
W19	5	X	X	X	X	4	X	X	X	6	X	X	X	X	X
W20	X	4	X	X	X	5	X	X	X	X	6	X	X	X	X
W21	X	X	3	X	X	6	X	X	X	X	X	6	X	X	X
W22	X	X	X	2	X	7	X	X	X	X	X	X	6	X	X
W23	X	X	X	X	X	X	1	7	X	X	X	X	X	X	7
W24	X	6	X	X	X	X	X	2	X	7	X	X	X	X	X
W25	X	X	5	X	X	X	X	3	X	X	7	X	X	X	X
W26	X	X	X	4	X	X	X	4	X	X	X	7	X	X	X
W27	X	X	X	X	3	X	X	5	X	X	X	X	7	X	X
W28	X	X	X	X	X	2	X	6	X	X	X	X	X	7	X

Table 2-1: The routing and wavelength assignment for 15 nodes ring, the first column is the order of wavelengths, the first row is the re-ordered node locations which correspond to the real positions in the ring, such as the node 9 in re-ordered ring is the node 2 in Figure 2-7.

Note how the addition of new nodes might increase the initial number of spans traversed by a given wavelength channel and consequently degrade its end-to-end performance. For example, the worst case scenario longest path channel λ_1, shown in Figure 2-7, which initially links only the adjacent nodes at the initial deployment of a 3-node ring (traverses a maximum of only one span), will eventually cross over 7 nodes (traverses a maximum of 8 spans) to maintain the same connectivity when the ring size has evolved from 3-nodes up to 15 nodes.

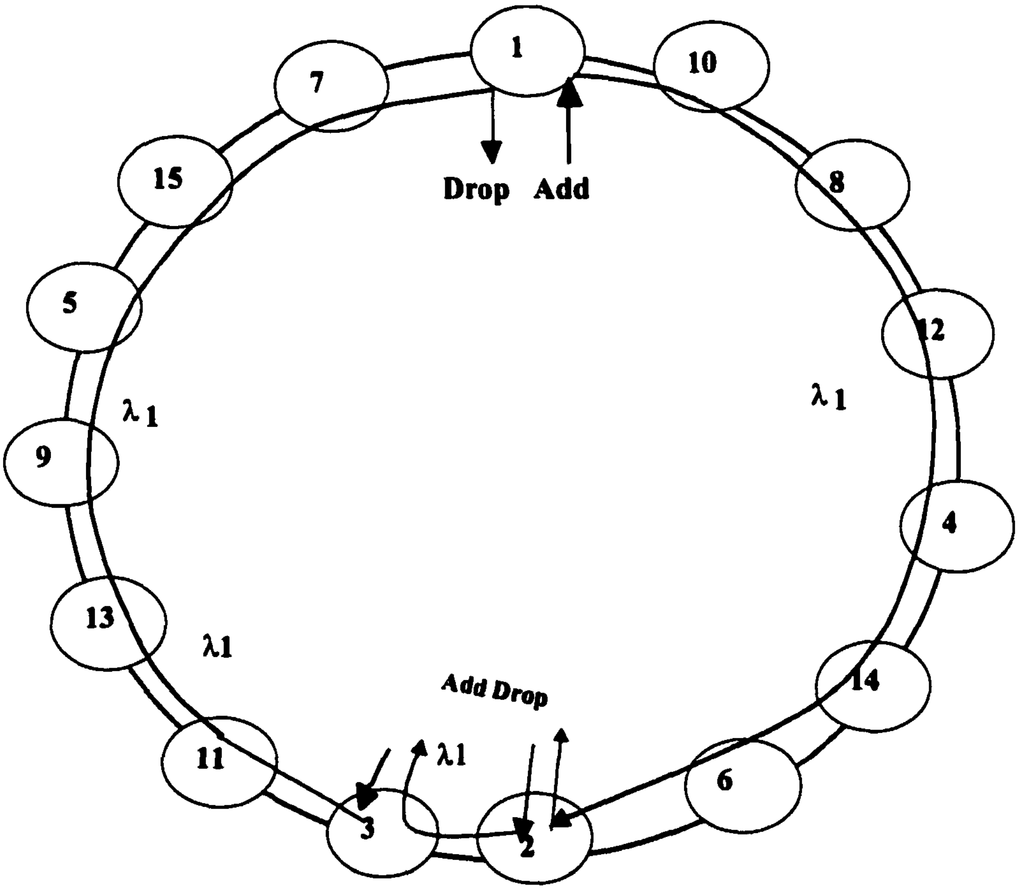


Figure 2-7: The worst possible scenario for ring network evolution

Assume that wavelengths are arbitrarily assigned to the ring nodes and that the obvious channel-wavelength allocation [($\lambda_1, \lambda_2, .., \lambda_{28}$) = (1538.2, 1540, ..., 1559.8) nm] is used, where the 1538.2-1559.8-nm spectral region is the amplifier band assigned to the signals wavelength. In this case, the longest path channel λ_1 is assigned the 1538.2 nm signal wavelength. However, the physical characteristics of the EDFAs used here is such that the 1538.2-nm signal wavelength has the lowest intrinsic amplifier gain (and consequently the lowest SNR) from among all the 28 signal wavelengths. This would further degrade the end-to-end performance of the longest path channel λ_1, with the result that its output SNR, as will be shown, may not be adequate for multiGb/sec operation. Thus, signal wavelength with the highest SNR from among all of the 28-wavelength signals may thus be assigned to the longest path channel λ_1 in order to maintain an adequate end-to-end channel performance. Using the same reasoning, signal wavelength with the lowest SNR from among all of the 28-wavelength signals may be assigned to the shortest path channel.

What is needed is an intelligent Networking Planning and Optimization Tool (NPOT) that interrelates the networking layer wavelength assignment algorithm with the physical layer transmission impairments for best overall system performance. The NPOT works as follows:

Step 1: Develop a wavelength assignment matrix that satisfy requirement # 1, from which locate those wavelengths with the longest possible total span length around the ring and its corresponding number of cascaded EDFAs.

Step 2: Optimize the performance of the EDFAs to be used across the ring, in terms of maximum gain, gain flatness, and lowest noise figure, for the total number of wavelengths (including those that are expected to be used in the future and won't be in service at the initial deployment) over the number of cascaded EDFAs determined in step1.

Step 3: Observe the SNR evolution of the dropping wavelengths at different expansion stage of the ring in each node.

Step 4: Optimize the wavelength assignment algorithm (determined in step 1) by reassigning wavelength signals with the highest SNR for the longest path channels and those with the lowest SNR for the shortest path channels.

2-3-3. Node Architecture

Figure 2-8 shows a block diagram of an optical node. The WDM signal coming from working path will pass the optical switch first followed by wavelength demultiplexer. Some of the wavelengths will be dropped at the node and some of them just pass through it. The wavelengths dropped will be terminated at each SONET BLSR ADM. The number of SONET ADM is equal to the number of wavelength dropped in this node. The outgoing signals will pass the following optical switches before leaving the node.

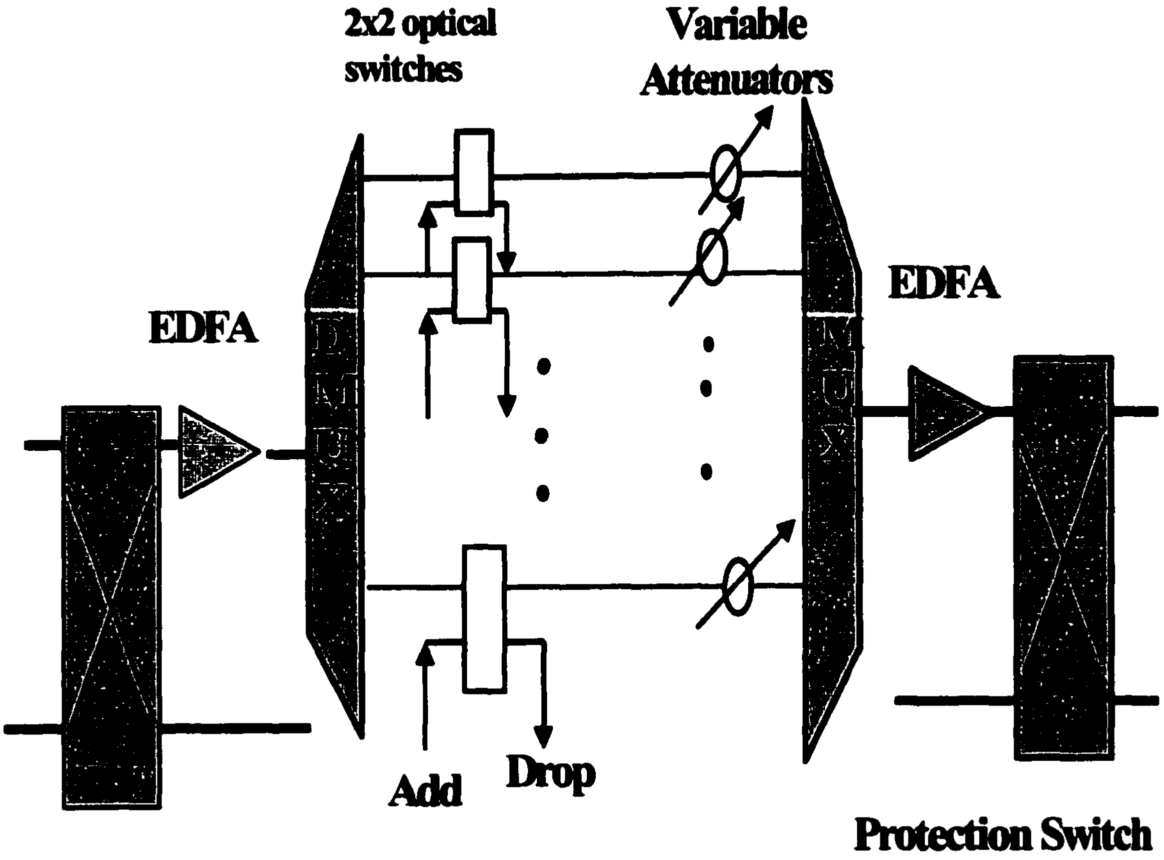


Figure.2-8: Node architecture for working ring

The system model consists of 28-10 Gb/sec WDM channels spaced 100-GHz apart in the 1538.2 to 1559.8-nm amplifier band. The preamplifier is used to compensate the loss that is caused by DMUX/MUX, and optical switches. The poster-amplifier compensates the span loss during transmission. The amplifier is the critical component, it should has low-noise and high gain. In order to get flatted gain spectrum, gain equalization technologies are used.

In our system model, each amplifier in the network is a 2-stage EDFA, optimized at 15 m 1st stage and 40 m 2nd stage, with an isolator in between. Each single stage amplifier is co-directionally pumped with 90 mW of pump power at 980-nm. The input signal levels are -18 dBm/channel at the input of the first amplifier. Variable optical attenuators are used for gain equalization. The signals at each node are dropped/added using commercially available DMux/Mux filters. Each node drops seven wavelengths and adds seven new signals (same wavelengths) at –18 dBm/channel, according to the dropping plan. The average dual-stage EDFA gain = 22 dB compensates for the total system loss including Mux/demur insertion loss, Variable optical attenuators loss, optical switches loss, and a fiber span loss of 10 dB, which allows about 40 km separation between successive nodes.

The signal and ASE power accumulation along the EDFA chain is determined based on the spectrally resolved numerical model of Refs.[9] The accumulated optical SNR reported here is the ratio between the signal level and the accumulated ASE noise power in a 0.2-nm optical bandwidth. The end-to-end system performance is estimated from the optical SNR, which must be more than 18 dB to achieve a bit-error rate (BER) of 10^{-14} at 10 Gb/sec.[10]

2-3-4. Simulation Results

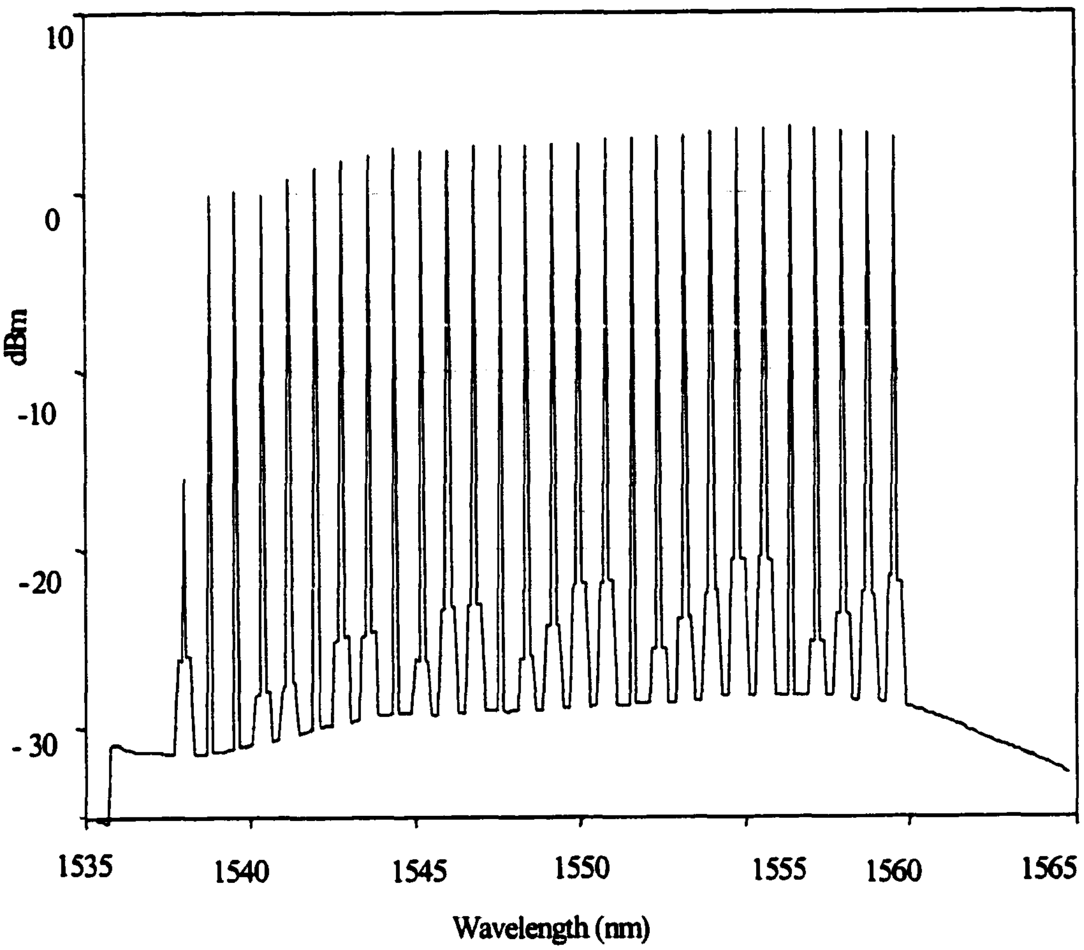
Figure 2-9 shows the output signal levels and noise spectra at node 3 for two cases:

Case 1: wavelengths are arbitrarily assigned to the ring nodes and the obvious channel-wavelength allocation [(λ_1, λ_2, λ_{28}) = (1538.2, 1540...1559.8) nm] is used. In this case, the longest path channel λ_1 is assigned the first wavelength slot (1538.2-nm).

Case 2: The NPOT is used to reassign the channel-wavelength allocation as follows: [(λ_1, λ_2, λ_{28}) = (1551, 1540,...,1538.2,...,1559.8) nm]. Note how the NPOT reassigns the longest path channel λ_1 to wavelength slot # 16 (1551-nm). The 1551-nm signal wavelength has both the highest amplifier gain and SNR, and still maintains the highest gain and SNR after emerging from 14 cascaded EDFAs. Note also that Wavelength slot # 1 (1538.2-nm) has been reassigned to the shortest path channel (channel # 28) which just connects two adjacent nodes.

We chose node 3 because in the example presented here, it represents the worst case scenario due to: 1) it contains the optical signal at the shortest wavelength (1538.2-nm), corresponding to the lowest amplifier gain; 2) Node 3 drops the signal after it has traversed the longest cascade of amplifiers (14 EDFAs), being added at node 1 and traversing 7 nodes before dropping at node 3. As can be seen from Figure 2-9, in case 1, at λ_1 = 1538.2-nm, both the output signal level (-16 dBm) and the optical SNR (10 dB) are insufficient for 10 Gb/sec operation. However, in case 2, at λ_1 = 1551-nm, both the output signal level (0.5 dBm) and the optical SNR (21 dB) are sufficient for 10 Gb/sec operation.

(a) NPOT is not used



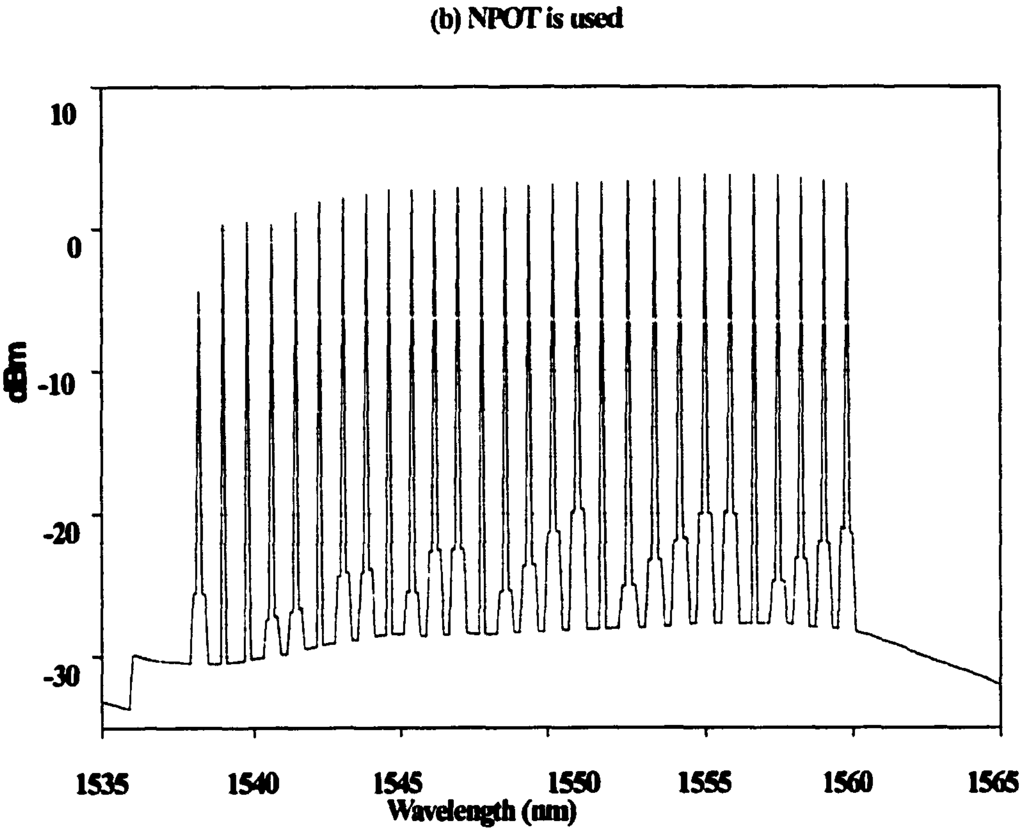


Figure 2-9: (a) and (b) illustrate the signal spectra w/o using NPOT

2-4. Conclusion

A novel full-meshed connected ring expansion methodology and planning tool have been proposed. The planning tool relates the physical layer wavelength characteristics with network layer wavelength assignment to get the best system performance. A 3 to 15 expansion ring has been studied that have demonstrated a dramatic system SNR improvement when the proposed planning tool was used. This study has suggested that the network operator need to consider the long-term expansion plan before selecting the first set of wavelengths for the access full-mesh ring.

2-5. References

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CHAPTER 3

ULTRA-HIGH SPEED DWDM-BASED BACKBONE TRANSPORT NETWORK FOR NEXT GENERATION INTERNET

3-1. Introduction

Wavelength division multiplexing (WDM) technology has emerged as the leading solution for high-speed transmission application and has been the demanding technology of next generation networks. Aggregate bandwidth required by the Internet in the US by the year 2005 is expected to be in excess of 35 Terabytes/sec. To meet this anticipated need, an ultra high speed Internet backbone transport network, capable of supporting up to a Tb/sec traffic capacity is required. Specifically, this chapter examines, through computer simulation and modeling, the technological requirements and assesses the performance analysis and feasibility for implementing ultra-high speed NGI backbone transport network fabric based on WDM technology. We will evaluate the end-to-end performance of a ring-based topology backbone transport network.

A ring topology has been selected here for two main reasons: 1) It is considered as a powerful candidate for introducing DWDM into the access environment due to its inherent reliability.[1-3] And 2) A mesh-based backbone transport network topology can be partitioned into several smaller inter-connected rings. Thus, a ring topology will constitute the fundamental building block for NGI backbone transport network facilities.

3-2. Key Technological Requirements

The design of WDM systems and optical networks is currently constrained by the limited bandwidth available from erbium-doped fiber amplifiers (EDFAs). The usable bandwidth is limited to about 12-nm because of the highly structured gain spectrum. With gain equalization filters (GEFs),[4] this gain bandwidth can be extended to between 35 and 40 nm (about 1525 to about 1565 nm).[6-7] Since the gain drops sharply below 1525 nm or above 1565 nm, it is not practical to further increase the gain bandwidth with GEFs. As we scale up the number of wavelengths in WDM systems, the spacing between wavelengths will decrease and the crosstalk among channels will increase. This system crosstalk will eventually limit the scaling capacity of WDM networks required for the efficient implementation of the NGI backbone transport facilities. In addition, current long haul WDM transport systems have very limited wavelength add/drop multiplexer (WADM) capabilities, which is a key limiting factor hindering the feasibility of flexible WDM backbone transport facilities.

To further increase capacity with a channel spacing compatible with practical filtering technology, as well as to increase wavelength routing network capability, the number of channels must grow. It would also be advantageous to be able to access one or more of the optical channels at any amplifier site in a WADM configuration. The

WADM configuration must include both fixed and reconfigurable optical add/drop multiplexers. This will require a new design of ultra broad-band silica-based EDFA configurations, that are the focus of this chapter, with flexible and scaleable optical add/drop capabilities.

Two key technological issues need to be addressed before the successful implementation of the proposed ultra-high speed NGI backbone WDM transport network fabric:

1. Novel architectures that offer a possible route to ultra-broad band amplifiers capable of providing 60-80 nm of optical bandwidth based on erbium-doped silica fiber must be developed. Using these ultra-broad band EDFAs, the number of WDM channels can then grow to about 80-100 channels while keeping a channel spacing compatible with practical filtering technology.

   One possible solution for broad-band EDFAs is achieved using new materials. Erbium-doped fluoride fibers have been shown to provide a gain bandwidth of 24 nm without GEF.[4] Erbium-doped tellurite fibers have also been reported to be a promising candidate.[5] However, the gain spectrum of tellurite EDF is highly non-uniform and many other properties need to be investigated before such fibers can be qualified for practical applications. Alternatively, new architectures offer a possible route to broad band amplifiers based on erbium-doped silica fiber. Previous work has shown that optical gain can be obtained in erbium-doped silica fibers in the long wavelength range between 1570 and 1600 nm (called L-band here).[6-7]

This chapter examines and develops a novel two-band EDFA configuration capable of providing as large as 80-nm of optical bandwidth using only silica-based EDFAs. This is achieved by combining the gain in the conventional wavelength range between 1525 and 1565 nm (called C-band in this chapter) and that in the long wavelength range between 1570 and 1610 nm (called L-band here). Each configuration consists of two parallel dual-stage silica-based EDFA, where each dual-stage is independently optimized. Such configurations offer a practical route to remove the bandwidth limitation which currently constrains the design of flexible WDM systems and networks. With 80 nm of bandwidth, this EDFA configuration will be able to accommodate 100 WDM channels with the proposed ITU standard channel spacing of 100GHz.

Specifically, this chapter will investigate and develop ultra wide-band gain-flattened and stabilized silica-based EDFA configuration with flexible and scalable Wavelength Add/Drop (WADM) capabilities. The WADM is assumed to be located between the dual-stage EDFA of each band. Each WADM consists of short-period fiber grating filters along with circulators and a given number of wavelength selective elements depending on the number of wavelengths to be added/dropped, to perform the WADM capabilities. These configurations must be capable of satisfying the following:

- Low-noise and high output power.
- Gain flatness should be independent of the operating conditions (signal and pump power levels, etc.).
- Maintain constant per-channel output power with a minimally degraded SNR, regardless of the number of channels present, over a wide dynamic range of input signal levels.
- Amplify and add/drop any number of wavelengths ranging from one to perhaps 25 depending on the wavelength assignment plan.
- Flexible for graceful in-service upgrade to a maximum of 100 WDM channels along with the smooth evolution in increasing the bit rate per channel from OC-12 to OC-192.

2. A novel practical filtering technology that is compatible with the channel spacing must also be developed and investigated. Specifically, this work examines novel WDM switching technologies using long/short period fiber grating filters. The feasibility of using one new feature, crucial for broadband long-haul WDM transmission systems, to equalize (flatten) the passband of cascaded EDFAs will be examined. Long-period fiber gratings will be used to flatten the gain and broaden the optical bandwidth of a two-stage mid-amplifier pumped EDFAs.

3-2-1. Two-band EDFA Architecture

Fig. 3-1 shows an architecture of the proposed two-band EDFA configuration. It consists of two parallel dual-stage silica-based EDFA, where each dual-stage is independently optimized first for output power and secondly for gain flatness over the 40-nm signals bandwidth. Circulators and broad band fiber Bragg gratings that reflect the C-band are used to demultiplex and multiplex the two bands before and after amplification, respectively. Thus, the two bands are amplified separately and are recombined afterwards. The circulators also act as an isolator. Both bands use the same type of silica-based fibers but with longer amplifier lengths for the L-band.

3-2-2. WADM Architecture

A WADM is assumed to be located between the dual-stage EDFA of each band, as shown in Figure 3-1. Each WADM, as shown in Figs. 3-2 and 3-3, consists of short-period fiber grating filters along with circulators and a given number of wavelength selective elements depending on the number of wavelengths to be added/dropped at a given node, to perform the WADM capabilities. For a fixed WADM configuration, the number of short-period grating filters will depend on the wavelength drop/add assignment plan. However, for a fully reconfigurable WADM, the number of short-period grating filters should equal the total number of wavelengths passing through the EDFA configuration. We will examine two techniques to investigate the potential and feasibility of programmable and/or tunable short-period grating filters in the following paragraphs.

Another critical criterion that must be met in the design of our proposed EDFA configuration is its flexibility for graceful in-service upgrade to a maximum of 100 WDM channels along with the smooth evolution in increasing the bit rate per channel from OC-12 to OC-192.

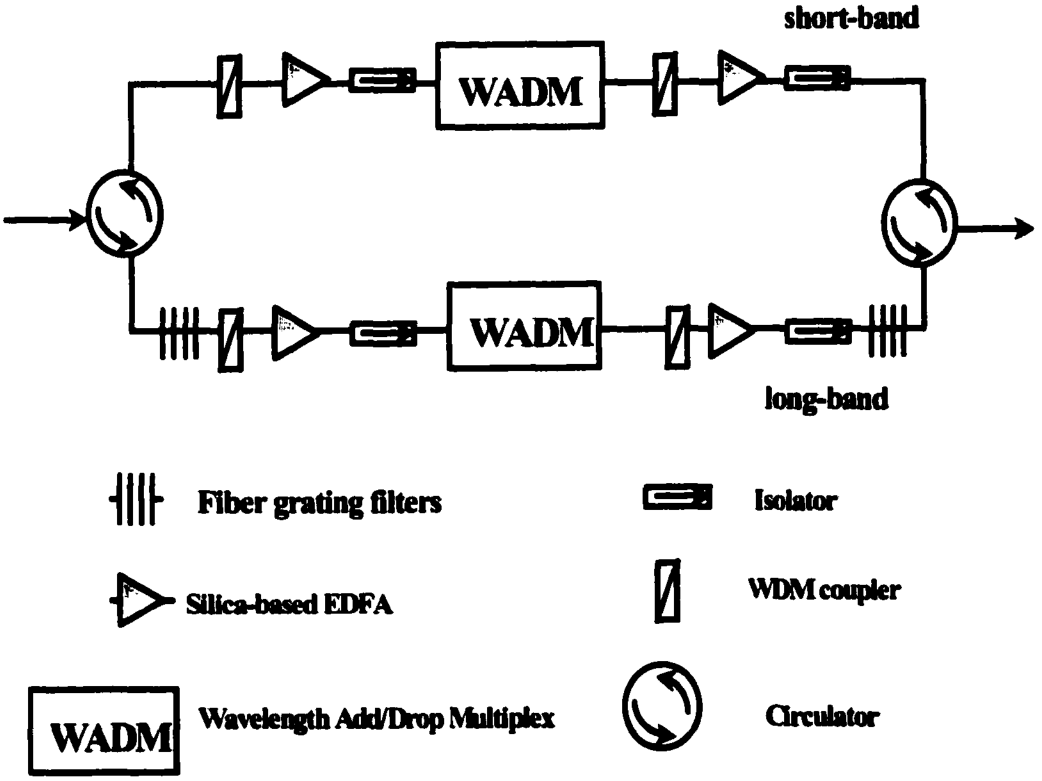


Fig.3-1: Schematic diagram of one architecture of proposed dual-band EDFA Config.

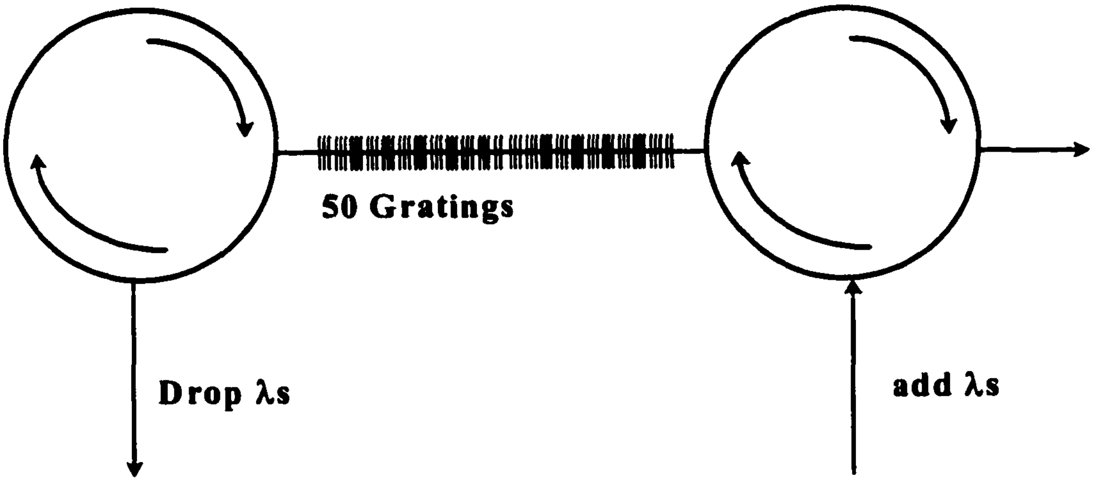
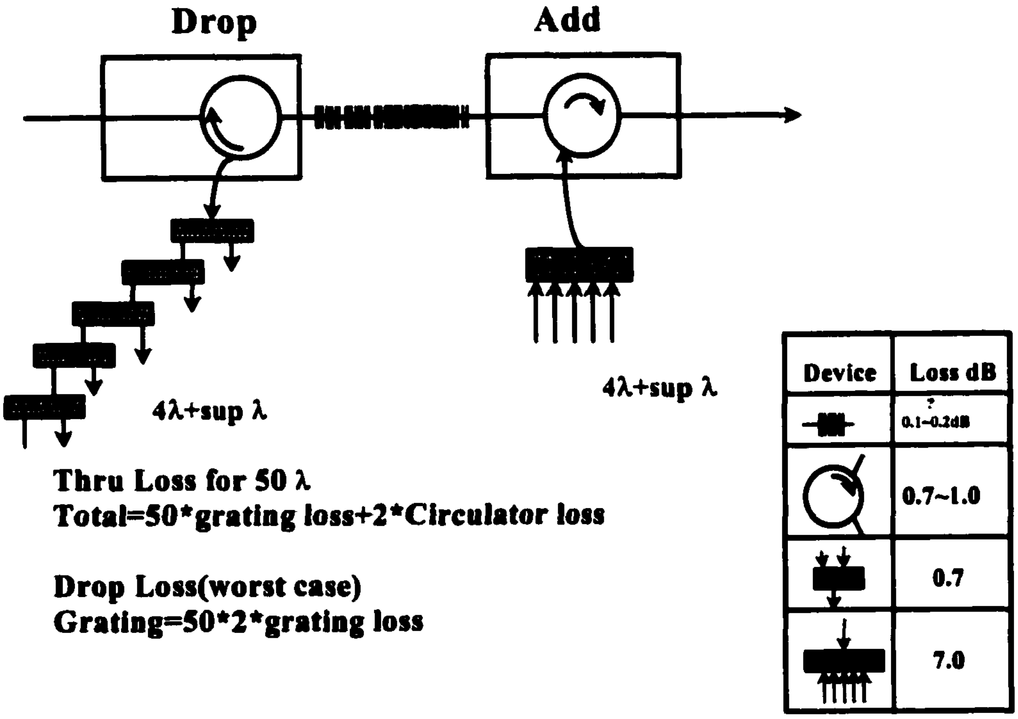


Figure 3-2: Add/Drop Design for 50 λ



Thru Loss for 50 λ
Total=50*grating loss+2*Circulator loss

Drop Loss(worst case)
Grating=50*2*grating loss

Figure 3-3: The fixed add/drop method

There are two types of building blocks of WADM are proposed: the S-type building block and Bragg wavelength tuning building block.[11] Figure 3-4 shows the series type of building block. The series of FBG elements and 2x2 optical switches are used with each FBG inserted between two 2x2 optical switches, each optical switch has one of the "cross" and the "bar" operation states at one time. Switching two 2x2 optical switch's, one in front of and one after the FBG element, to the "cross" state, the passed through channel signal will be reflected by the connected Fiber Bragg Grating element, then leaving from the dropped port of circulators. In the mean time, other crossed-connected channel signals can be spatially passed through the FBG chain to another fiber link. When two or more 2x2 optical switches are properly arranged in the S-type building block, multiple channel adding/dropping can then be realized. Fig. 3-4 (b) illustrates that the wavelengths λ_1 and λ_2 are simultaneously reflected and thus passed-through the 2x2 WXC when the first and the third optical switches are in the "cross" states and other optical switches are in the "bar" states. For rearrangeable add/drop operation, the number of required 2x2 optical switches, $U=m+1$, and total number of required FBG's, $Q=m$, respectively. Here m refers to the total number of wavelengths passing Add/Drop module. The feasibility of the proposed S-type building block has been proved by.[11]

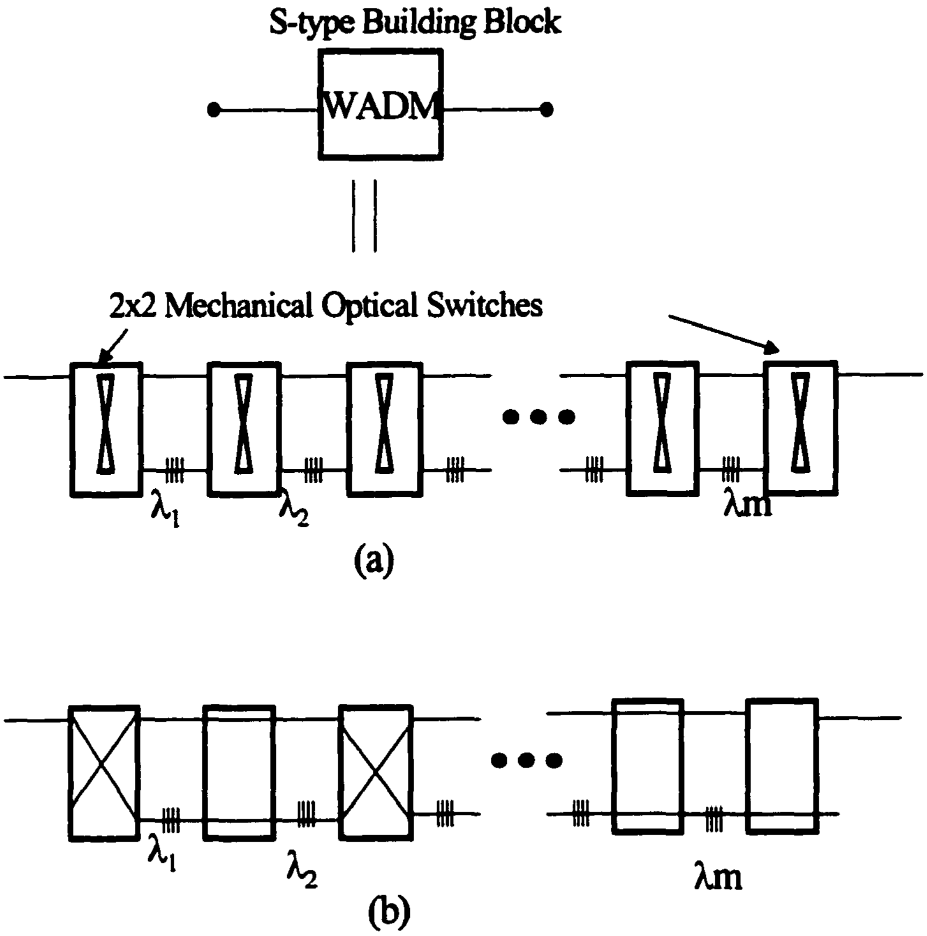


Figure 3-4. The (a) schematic diagram of the series S-type building block "FGR" and (b) illustration of its operating principle.

Figure 3-5 shows the nonswitched voltage-controlled building block, in which a series of FBG's with appropriate control devices are used but with no more optical switches. The voltage-controlled narrow band fiber gratings with high reflectivity to the targeted wavelengths and low transmission loss for other bypassing wavelengths are used to cooperate the circulators to implement the add and drop functionality. Here WADM consist of FBG filers to provide low cross-talk performance, and no signal degradation is occurred.[10] The FWHM (i.e., 3-dB passband width) of each FBG should be large enough to cover the corresponding channel signal with high reflectivity and low out-of-band transmission loss.

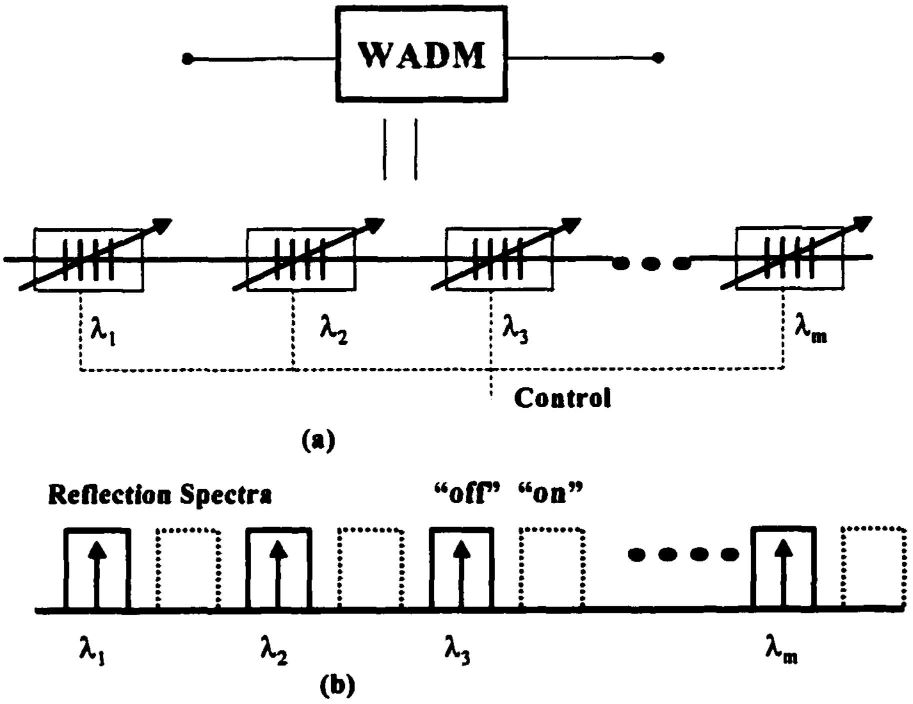


Figure 3-5: The (a) schematic diagram of the FGR block and (b) illustration of its operating principle.

The voltage controllers are used to control the reflected FBG window's position to selectively choose the added or dropped wavelengths. The voltage-driven piezoelectrical transducer (PZT) devices or the stepping motors can be used to implement the central wavelength-shift control of each FBG by using compressive stress on the FBG. In Ball and Morey's experiment,[12] the wavelength tuning range can achieve ± 50nm, and a wavelength resolution of ± 2pm. When the voltage is released, the Bragg fiber grating windows (in Figure 3-5 (b)) will be in OFF status, and when the voltage is supplied, the spectra window will shift to the desired position, we consider this status as ON. The voltage-controlled fiber grating has two states: ON and OFF. In OFF status, the grating window will locate at the dropped wavelength, both signal and ASE at that wavelength get reflected to drop port through circulator without passing to next EDFA. In ON status, the signal at wavelength λ will be passed, the voltage-controlled grating window will shift 0.4 nm (the half of the channel spacing) to right, so that ASE at λ+0.4 nm will be disappeared from the next EDFA. This design can significantly reduce the ASE accumulation and improve the SNR. For the add wavelengths, they are added through the add port of circulator, reflected by WADM, and fed into WDM system through another arm of circulator. Compared with the S-type building block, the Bragg wavelength tuning building block can reduce the insertion loss, which is caused by the optical switches, and increase the optical SNR. Therefore in our node structure, the Bragg tuning building block is used.

3-2-3. Gain Equalization

Since the amplification of a wavelength division multiplexed (WDM) signal by non-equalized erbium-doped fiber amplifiers (EDFAs) may result in signal distortion and poor signal to noise ratio performances, several methods, either intrinsic or extrinsic, have been proposed to equalize the gain of EDFAs. Intrinsic methods consist of modifying the spectroscopic properties of erbium ions by a change in codoping ions or glass matrix. Alumino-silicate[13] or fluoride-based[14] glasses are such host matrixes that improve the flatness of EDFA gain spectra. However, intrinsically equalized amplifiers are accurate over a limited bandwidth. Extrinsic methods equalize the gain by making use of a filtering device connected in series with the EDFA. In-fiber filters that have been previously demonstrated include acoustooptic tunable filters,[15] long-period gratings[16] or blazed gratings.[17] The main limitation of an acoustooptic filter is its high RF power consumption. Long-period and blazed gratings are sensitive to environmental conditions since they rely on coupling from guided to nonguided modes. Furthermore, their manufacturing complexity rapidly increases when the equalization bandwidth is extended. Gautheron *et. al.*[18] have shown that Bragg gratings placed after each amplification stage can equalize the gain of cascaded EDFAs. However, each of the narrow-band filters used was attenuating a single channel and therefore most of the amplified spontaneous emission (ASE) was transmitted. We use gain equalization performed using various configurations of spectrally designed Bragg gratings in the front of the latter stage amplifier.

Long-period fiber gratings will be used to flatten the gain and broaden the optical bandwidth of EDFAs. The ideal fiber Bragg grating filter spectrum is computed based on the following optimization method.

1. For a given total input power, $P_{in}^{(2)}$ at the input of the second stage EDFA, determine the intrinsic WDM gain spectra. $G_{intrinsic}(\lambda)$.
2. Determine the input signal level/channel $P_{in,flat}^{(2)}(\lambda)$, required to produce a at output spectrum over the desired signals bandwidth at the output of the second stage by first

using the normalized WDM signal gain spectra, $G_{normalized}(\lambda)$, defined as $G_{normalized}(\lambda) = G_L / G_{intrinsic}(\lambda)$, then

$$P^{(2)}_{in,flat}(\lambda) = G_{normalized}(\lambda) * P^{(2)}_{in} / \sum_{\lambda} G_{normalizd}(\lambda)$$

where G_L is the least-favored signal gain from among all of the signal wavelengths and

$$P^{(2)}_{in} = \sum_{\lambda} P^{(2)}_{in,flat}(\lambda)$$

3. Determine the first stage EDFA output power spectra, $P^{(1)}_{out}(\lambda)$.
4. Determine the transmission characteristic of the long period fiber grating, $T(\lambda)$, by using

$$P^{(1)}_{out}(\lambda) * (\text{total intra-stage loss}) * T(\lambda) = P^{(2)}_{in,flat}(\lambda)$$

3-3. Wavelength Assignment for 4-fiber Bi-directional Ring

For a bi-directional 4-fiber WDM ring with N nodes attached it, the full mesh connectivity is that each node N_i is connected to all other (N-1) nodes on the ring via the shortest paths. In order to find the minimum number of wavelengths required for full mesh connectivity, the general requirements for wavelength assignment are looking for the minimum number of connections that shares a single fiber link in a single direction, and avoiding any wavelength clash. Since we have the uniform traffic distribution for our ring topology, for any physical fiber link, the number of connections passing it is the same as the number of connections passing any other fiber link. Since the even number of nodes of the ring has different character as the odd number of nodes of the ring, the analysis differentiates between the cases of odd and even number of nodes attached to the ring:

Odd number of nodes on the ring ($N=N_{odd}$)

Since the shortest path always is chosen, the longest path in the ring with the odd number nodes consists of $\frac{N_{odd}+1}{2}-1$ segments. Here N_{odd} = odd number of nodes in the ring. Segment is defined as a link between two adjacent nodes on the ring. For a given segment, the nodes attached are named as 1 and 2. The number of connections, which originate from 1 and pass this single segment is $\frac{N_{odd}-1}{2}$. The other affected nodes which have connections traversing this segment are N_{odd}, N_{odd-1}, ..., $\frac{N_{odd}+1}{2}$. The number of connections which originate from these nodes is $\frac{N_{odd}-1}{2}-1$, $\frac{N_{odd}-1}{2}-2$, ... , 1.

Therefore the number of connections passing the single directional segment is

$$1+\ldots+i+\ldots+\frac{N_{odd}-1}{2}=\frac{\left(\frac{N_{odd}-1}{2}+1\right)\left(\frac{N_{odd}-1}{2}\right)}{2}=\frac{N_{odd}^2-1}{8} \qquad (3\text{-}1)$$

Since we need to avoid wavelength collision, i.e., optical signals simultaneously sharing a single fiber have to have different wavelengths. The minimum number of wavelengths W is equal to the number of connections passing each common fiber link, i.e., $W = \frac{N_{odd}^2 - 1}{8}$.

Even number of nodes on the ring ($N=N_{even}$)

In this case, the longest connection for interconnecting any two nodes will be equal to N/2 segments of the ring. It has the difference from the ring, which has the odd number nodes attached, the shortest path of the longest connection can be in either direction, such as in Figure 3-6, the connection from node 1 to node N/2 is the longest connection. It has two possible shortest paths: one is in clockwise direction, i.e., 1, 2, ..., N/2, another is in counterclockwise direction, i.e., 1, N,..., N/2. The analysis also differentiates between the case when N_{even} can be divided by 4 and the case when N_{even} can not be divided by 4.

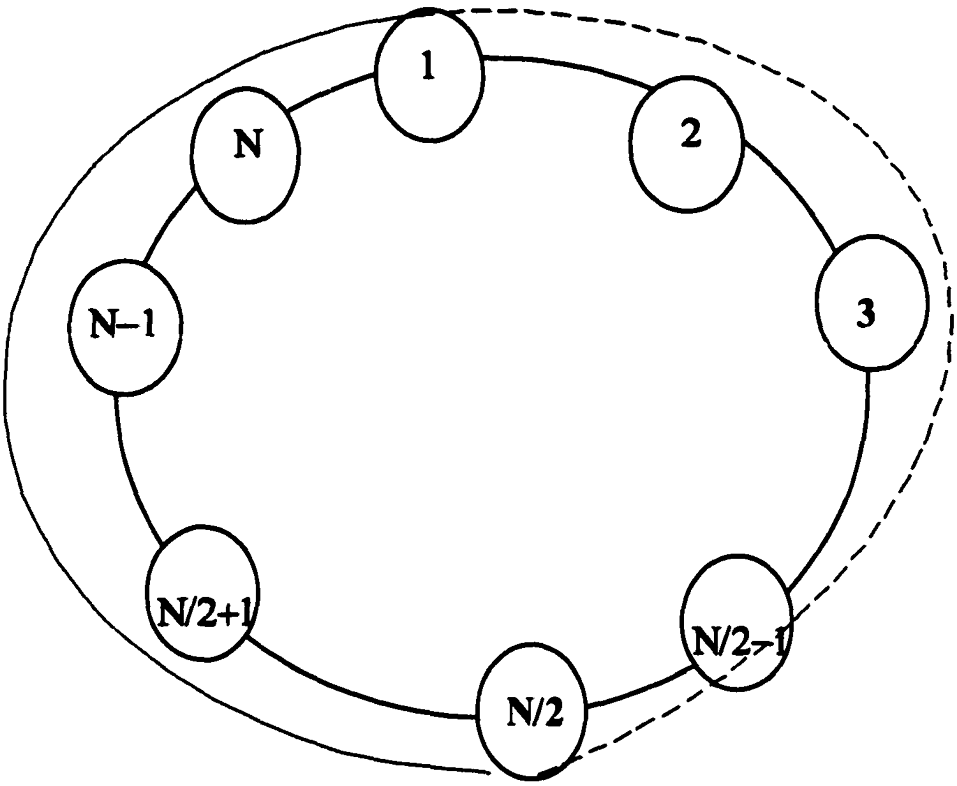


Figure 3-6 shows there are two possible shortest paths for the longest connection when there is even number of nodes on the ring.

As we know, the network with even number nodes is symmetric, we can evenly distribute the shortest paths of the longest connections into two directions. For example, if the longest connection, which connects node 1 and N/2, is routed in clockwise direction, then the next longest connection, which connects node 2 and node N/2+1, will be routed in other direction. The longest connection between node 3 and node N/2+2 also is routed in clockwise direction, and so on. For segment connecting with node 1 and node 2, the number of connections, which is originated from node 1, is N/2. The nodes, which will originate the connections passing this given segment, are N-1, N-2, ... , N/2+2, since the connection between N/2+1 is assigned to another direction without passing the given segment. The number of connections which originate from these nodes is $\frac{N_{even}}{2}-2, \frac{N_{even}}{2}-2, \frac{N_{even}}{2}-3, \ldots, 1$ respectively. If $\frac{N_{even}}{2}$ is even, The total number of connections passing the given segment is:

$$\frac{N_{even}}{2}+(\frac{N_{even}}{2}-1-1)+\frac{N_{even}}{2}-2+(\frac{N_{even}}{2}-3-1)+\ldots+1 \qquad (3\text{-}2)$$

$$\Rightarrow \frac{N_{even}}{2}+\frac{N_{even}}{2}-1+\frac{N_{even}}{2}-2+\ldots+1-\frac{N_{even}}{4}$$

$$\Rightarrow \frac{\frac{N_{even}}{2}\left(\frac{N_{even}}{2}+1\right)}{2}-\frac{N_{even}}{4}=\frac{N_{even}^2}{8} \qquad (3\text{-}3)$$

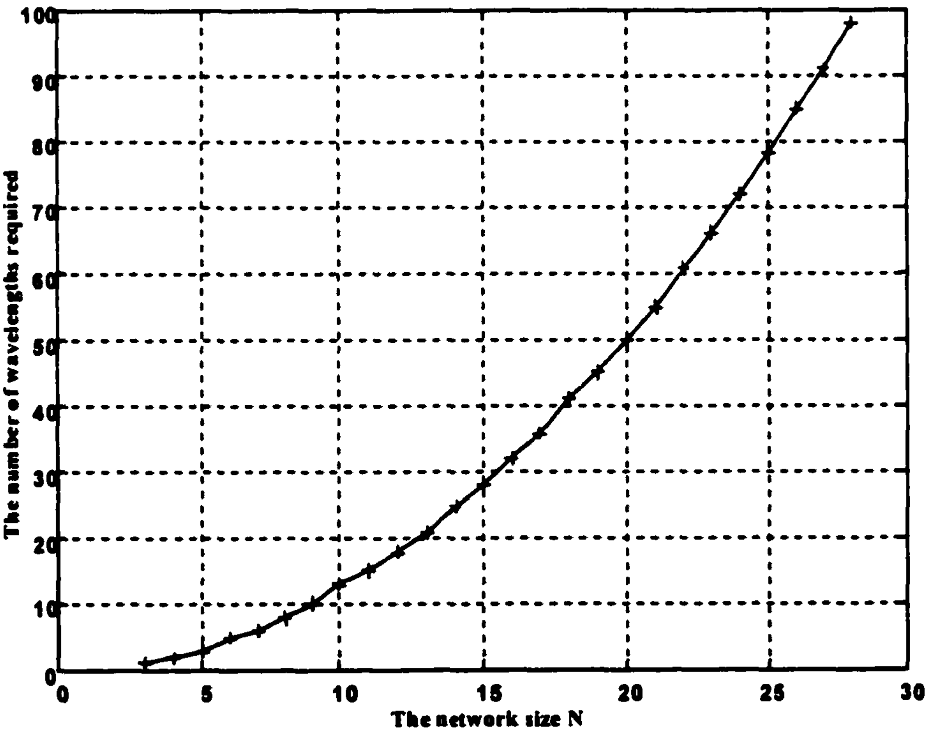
If $\frac{N_{even}}{2}$ is not divisible by 2, then (3-2) becomes:

$$\frac{N_{even}}{2}+(\frac{N_{even}}{2}-1-1)+\frac{N_{even}}{2}-2+\ldots+1-(\frac{N_{even}/2-1}{2})$$

$$\Rightarrow \frac{\frac{N_{even}}{2}\left(\frac{N_{even}}{2}+1\right)}{2}-\frac{N_{even}}{4}+\frac{1}{2}=\frac{N_{even}^2+4}{8} \qquad (3\text{-}4)$$

As shown in Figure 3-7 (a), 78 wavelengths are required for 24-node WDM ring to achieve full-meshed connectivity in our study case.

We take advantages of an existing wavelength assignment matrix approach for scalability problem, matrix approach has been found to work best for bi-directional ring wavelength assignment problem. The columns of the matrix represent the nodes on the ring, and the rows represent the wavelengths required for each connection from each node to every other node on the ring. Through appropriately filling the matrix, while following some simple rules, the optimal wavelength assignment has been obtained for an existing ring network which requires increasing the network size without disrupting the existing wavelength connections. We find that there only needs one wavelength for 3 nodes ring to achieve full-mesh connectivity (see Figure 3-7 (b)), if we keep growing network size by a single node at a time, without disturbing the existing wavelength assignments, and this single node can be added at any position, till the desired network size is obtained. Every time when we add a new node, the matrix is expended according to different rules for the even and odd number of network size (see in Chapter 2). Finally we can get the wavelength assignment of any size ring network.



(a)

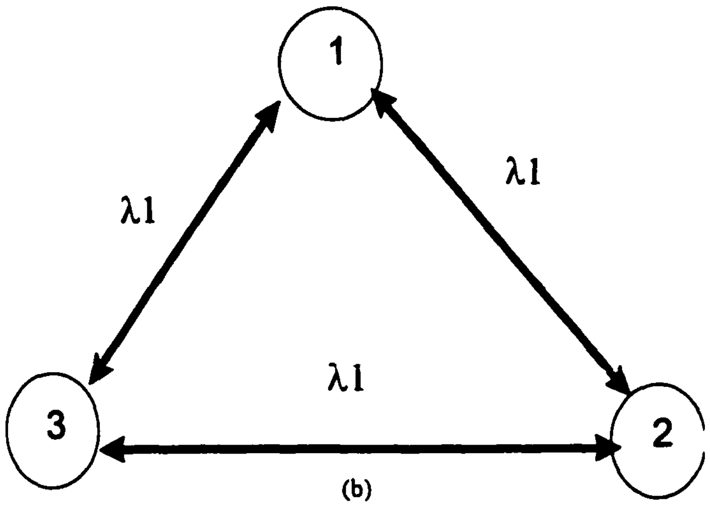


Figure 3-7. a) Simulation results of network size N, and the required wavelengths to achieve full–meshed connectivity (b): Network starts with 3 nodes 1 wavelength

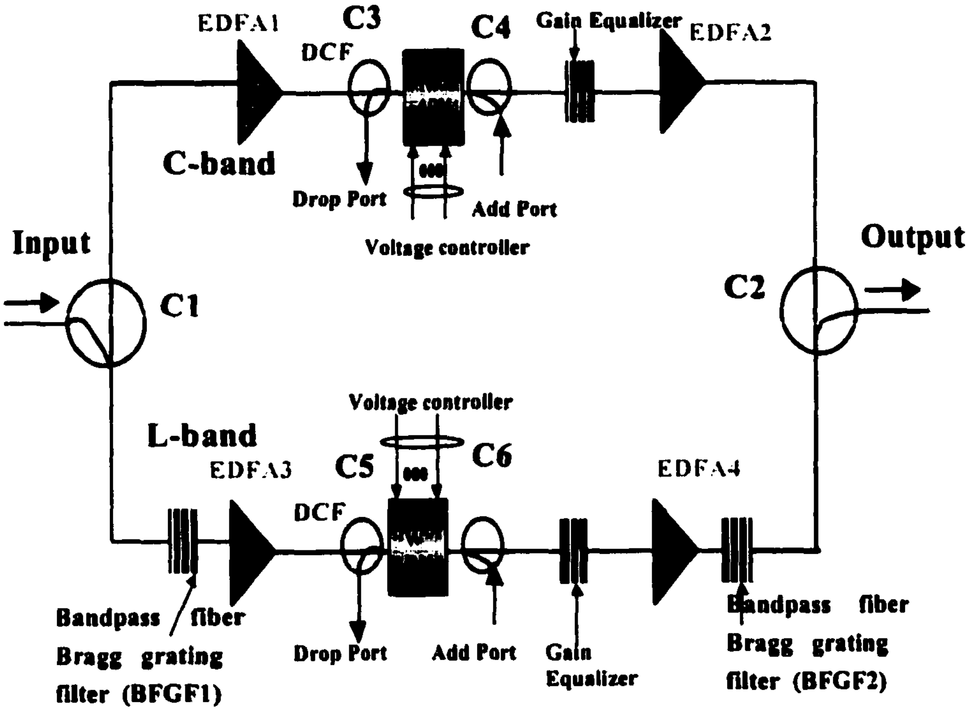
The wavelength assignment for 24-node ring is obtained by the above mentioned matrix filling approach. There is the routing table reflecting the add/drop/bypass wavelengths in each node. The connections are established according to the routing tables. Figure 3-8 shows the routing table for node 21, we use λ_1 as example to illustrate the content of table. λ_1 is added at node 16, it passes 5 hops to arrive in node 21, the number of hops represents how many spans the wavelength has been traveled to get into the current node. In our study case, $(\lambda_1, \lambda_2, ..., \lambda_{33})$ is mapping to (1537.4, 1538.2,..., 1563.8 nm). $(\lambda_{34}, \lambda_{35}, ..., \lambda_{78})$ is mapping to (1572.6, 1573.4,...,1608.6 nm). From Figure 3-8, we clearly see that the number of hops for $(\lambda_{56}, \lambda_{57}, \lambda_{58}, ..., \lambda_{66}, \lambda_{78})$ is 0, this means that these wavelengths are dropped at node 21, and are added into system again. The rest of wavelengths will bypass node 21.

	the added pos	# of hops		the added pos	# of hops		the added pos	# of hops		the added pos	# of hops
λ1	16	5	λ21	20	1	λ41	17	4	λ61	21	0
λ2	18	3	λ22	20	1	λ42	17	4	λ62	21	0
λ3	12	9	λ23	13	8	λ43	17	4	λ63	21	0
λ4	20	1	λ24	13	8	λ44	17	4	λ64	21	0
λ5	20	1	λ25	13	8	λ45	20	1	λ65	21	0
λ6	14	7	λ26	20	1	λ46	20	1	λ66	21	0
λ7	14	7	λ27	18	3	λ47	19	2	λ67	10	11
λ8	14	7	λ28	16	5	λ48	19	2	λ68	11	10
λ9	12	9	λ29	18	3	λ49	19	2	λ69	12	9
λ10	16	5	λ30	15	6	λ50	19	2	λ70	13	8
λ11	16	5	λ31	15	6	λ51	19	2	λ71	14	7
λ12	18	3	λ32	15	6	λ52	19	2	λ72	15	6
λ13	16	5	λ33	15	6	λ53	19	2	λ73	16	5
λ14	14	7	λ34	15	6	λ54	19	2	λ74	17	4
λ15	18	3	λ35	20	1	λ55	19	2	λ75	18	3
λ16	18	3	λ36	18	3	λ56	21	0	λ76	19	2
λ17	11	10	λ37	20	1	λ57	21	0	λ77	20	1
λ18	20	1	λ38	17	4	λ58	21	0	λ78	21	0
λ19	18	3	λ39	17	4	λ59	21	0			
λ20	16	5	λ40	17	4	λ60	21	0			

Figure 3-8: The routing table for Node 21

3-4. The System Model

The ultra-high speed DWDM-based ring network under consideration consists of 24 nodes. Successive nodes are separated by fiber loss of 10 dB, which corresponds to 40 km x 0.25 dB/km. Seventy-eight wavelengths are needed to achieve full-mesh connectivity between 24 nodes, and as has been shown in section 3.3, 12 wavelengths are added/dropped at each node. The schematic diagram of the node structure is shown in Figure 3-9.



DCF : Dispersion Compensation Fiber

Figure 3-9: Our proposed node architecture by adopting WDM and FBG technologies

The system model consists of 78 WDM channels subdivided into two subbands, the C-band and the L-band. 33-channels are spaced 100-GHz apart in the 1537.4 (channel 1) to 1563.8-nm (channel 33) amplifier C-band and the remaining 45-channels are also spaced 100-GHz apart in the 1572.6 (channel 34) to 1608.6-nm (channel 78) amplifier L-band. Circulators and broad band fiber Bragg gratings that reflect the C-band are used to demultiplex and multiplex the two bands before and after amplification, respectively. Thus, the two bands are amplified separately and are recombined afterwards. Both bands use the same type of silica-based fibers but with longer amplifier lengths for the L-band.

The two-band EDFA configuration, shown in Figure 3-9, consists of two parallel dual-stage silica-based EDFA, where each dual-stage is independently optimized first for output power and secondly for gain flatness over the desired signals bandwidth. The C-band dual-stage EDFA used in the simulation is co-pumped with 78 mW of pump power at 980-nm in stage 1 and with 60.5 mW at 980-nm in stage 2. The L-band dual-stage EDFA is co-pumped with 185 mW of pump power in stage 1 and with 68.5 mW of pump power in the forward direction in stage 2 (see Figure 3-10). The design of both amplifier stages for each band was chosen to produce an average dual-stage net gain of about 13 dB.

	EDFA1 (C-band)	EDFA2 (C-band)	EDFA3 (L-band)	EDFA4 (L-band)
Input power per channel (dBm)	-15	-14	-15	-14
Forward Pump power (mW)@980nm	78	60.5	185	68.5
Amplifier length (m)	8.8	4.8	74	51

Figure 3-10: The configuration parameter setting of each EDFA in Figure 3-9

The alumino-germano silicate EDFA used in the simulation is a commercially available fiber designed for high output power. A long-period fiber grating filter gain equalizer is located between the stages of both the C and L arms along with an isolator and a DCF. The computed ideal filter transmission characteristics for each band, shown in Fig. 3-11 and Fig. 3-12 respectively, is determined based on the optimization method reported in section 3-2-3.

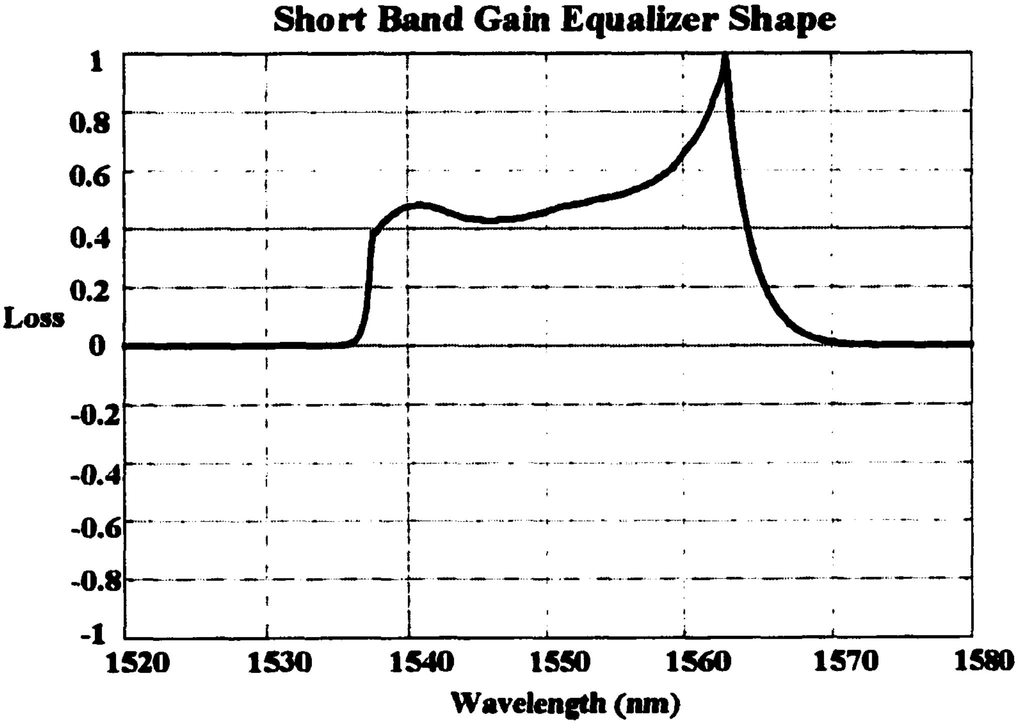


Figure 3-11: Transmission characteristics of long-period grating filter used in C-band EDFA

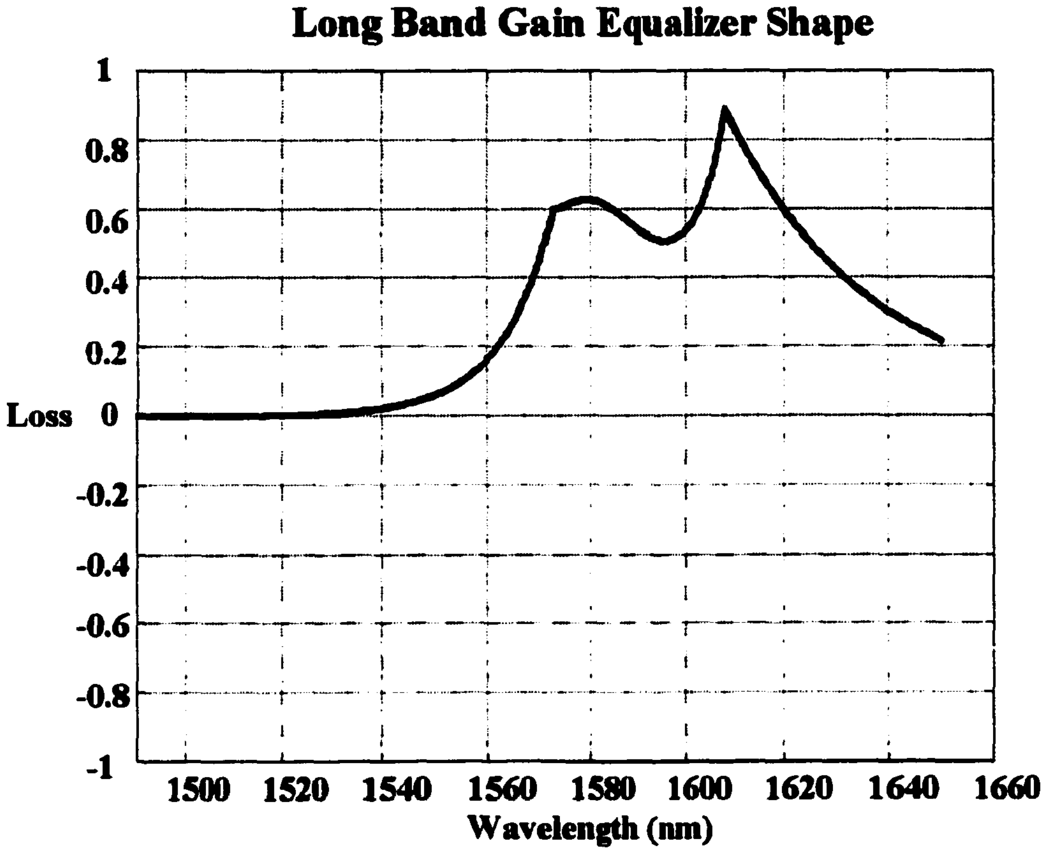


Figure 3-12: Transmission characteristics of long-period grating filter used in L-band EDFA

The total inter-stage loss for each node is the sum of 3 dB component loss, 2.55 dB DCF loss, and a varying WAD loss for each node.

3-5. Results and Discussion

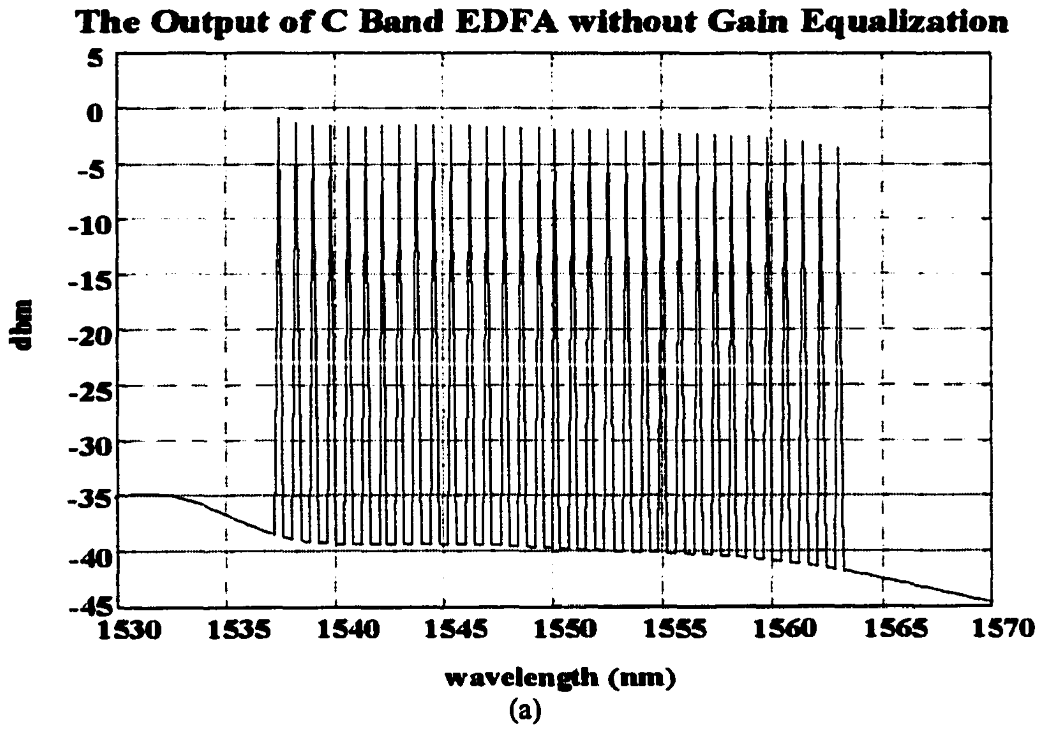
The ring transmission fiber consisted of twenty-four 40 km spans of standard SMF having an average chromatic dispersion of +17 ps/km-nm and an average attenuation of 0.25 dB/km. Each span is followed by 5.667 km of DCF, located between the dual-stage

EDFA of each band, having an average chromatic dispersion of -120 ps/km-nm and an average attenuation of 0.45 dB/km. The average dual-stage net gain of 13 dB is set equal the sum of the span loss between successive nodes 40km x 0.25dB/km=10dB, and the 3-dB input/output coupling loss.

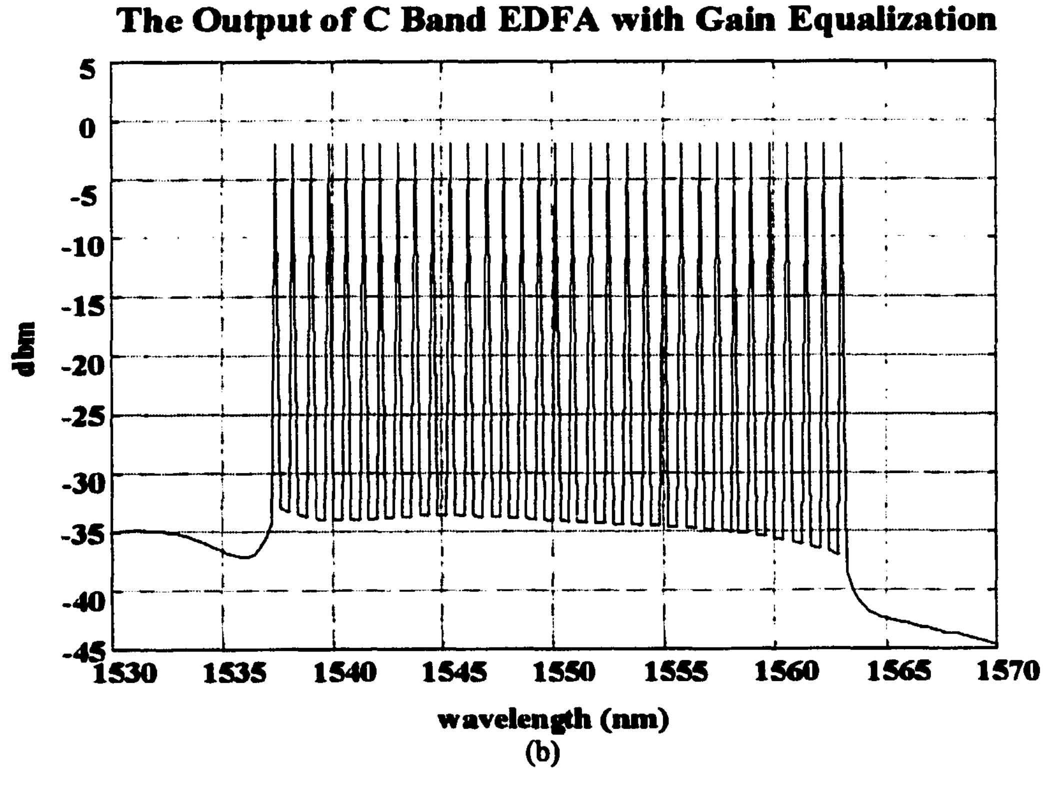
The signal and ASE power accumulation along the EDFA chain is determined based on the spectrally resolved numerical model of Ref.[6] The accumulated optical signal-to-noise ratio (SNR) reported here is the ratio between the signal level and the accumulated ASE noise power in a 0.2-nm optical bandwidth. The end-to-end system performance is estimated from the optical (SNR), which must be more than 18 dB (0.2-nm resolution) to achieve a bit-error rate of 10^{-14} at 10 Gb/sec.[20]

Figure 3-13 and Figure 3-14 show calculation of the output signal levels and the ASE power in a 0.2-nm optical bandwidth for both the C and L band, with and without gain equalization, respectively.

As can be seen from Figure 3-13, the intrinsic C-band dual-stage EDFA spectral gain variation of 2.61 dB ($G_{\max}(\lambda)=13.09$ dB, $G_{\min}(\lambda)=10.48$ dB) over 26.4-nm bandwidth is reduced to less than 0.03 dB (($G_{\max}(\lambda)=12.0268$ dB, $G_{\min}(\lambda)=12.00$ dB). It can also be seen from Figure 3-14 that the intrinsic L-band dual-stage EDFA spectral gain variation of 1.5386 dB ($G_{\max}(\lambda)=12.6186$ dB, $G_{\min}(\lambda)=11.08$ dB) over 36-nm bandwidth is reduced to less than 0.096 dB (($G_{\max}(\lambda)=12.046$ dB, $G_{\min}(\lambda)=11.95$ dB).



(a)



(b)

Figure 3-13: (a) The output of EDFA2 without gain equalizer; (b) The output of EDFA2 with gain equalizer.

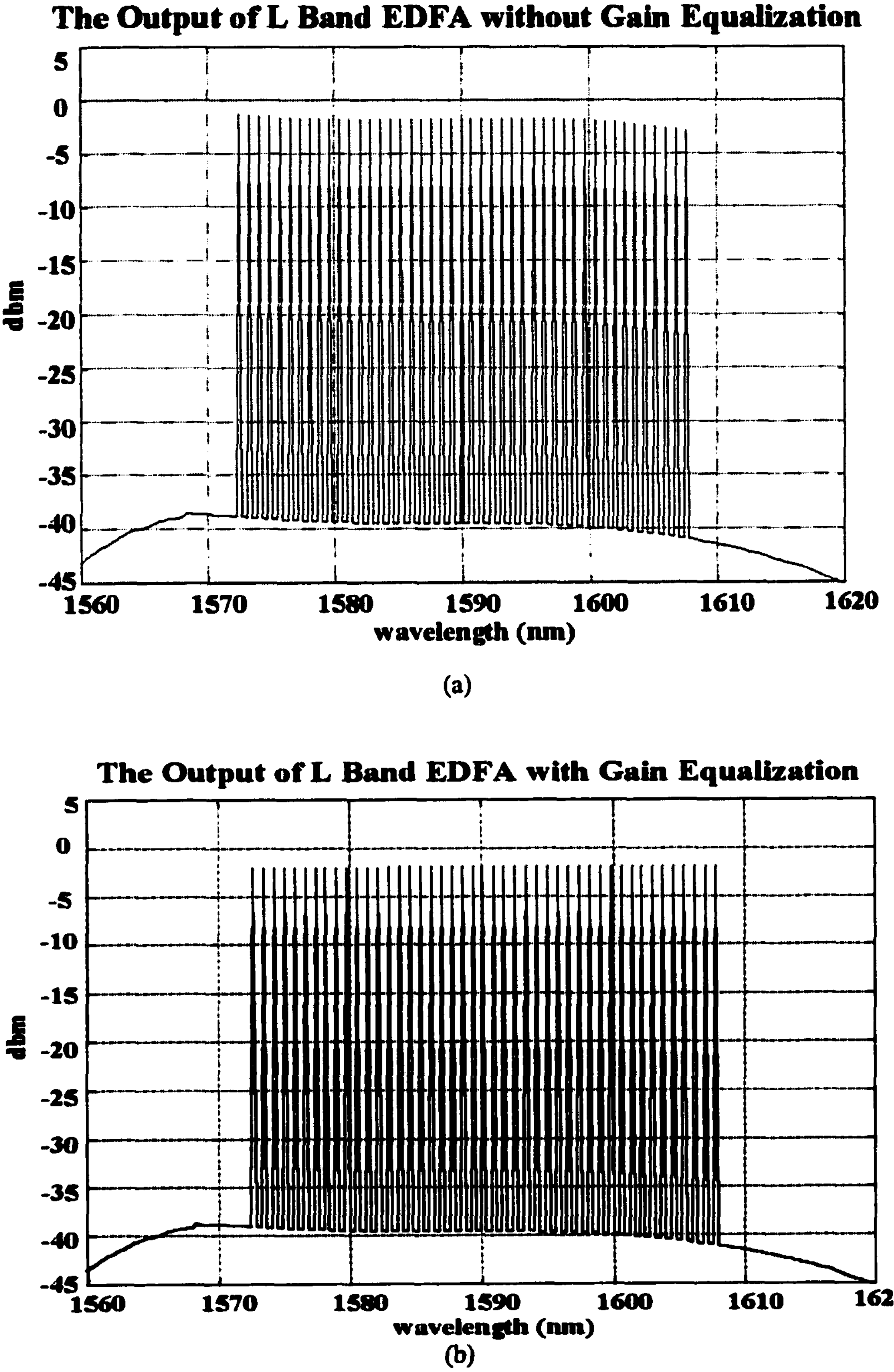


Figure 3-14: (a) The output of EDFA4 without gain equalizer; (b) The output of EDFA4 with gain equalizer.

Figure 3-15 and 3-16 show the output signal spectral and SNR at node 21. Node 21 was chosen because it corresponds to the worst case performance scenario among 24 nodes. The worst-case channels perform in this node are the C-band channel 3 ($\lambda_3 = 1539.0\,\text{nm}$) and the L-band channel 67 ($\lambda_{67} = 1598.0\,\text{nm}$). Note that λ_3 traverses 9 nodes while λ_{67} traverses 12 nodes.

As can be seen from Figure 3-15 and Figure 3-16, although the output signal levels are almost the same, however, the SNR is drastically different for each channel. Note, however the worst SNR value at channel 3 (23.15 dB) is still adequate for 10 Gb/sec operation.

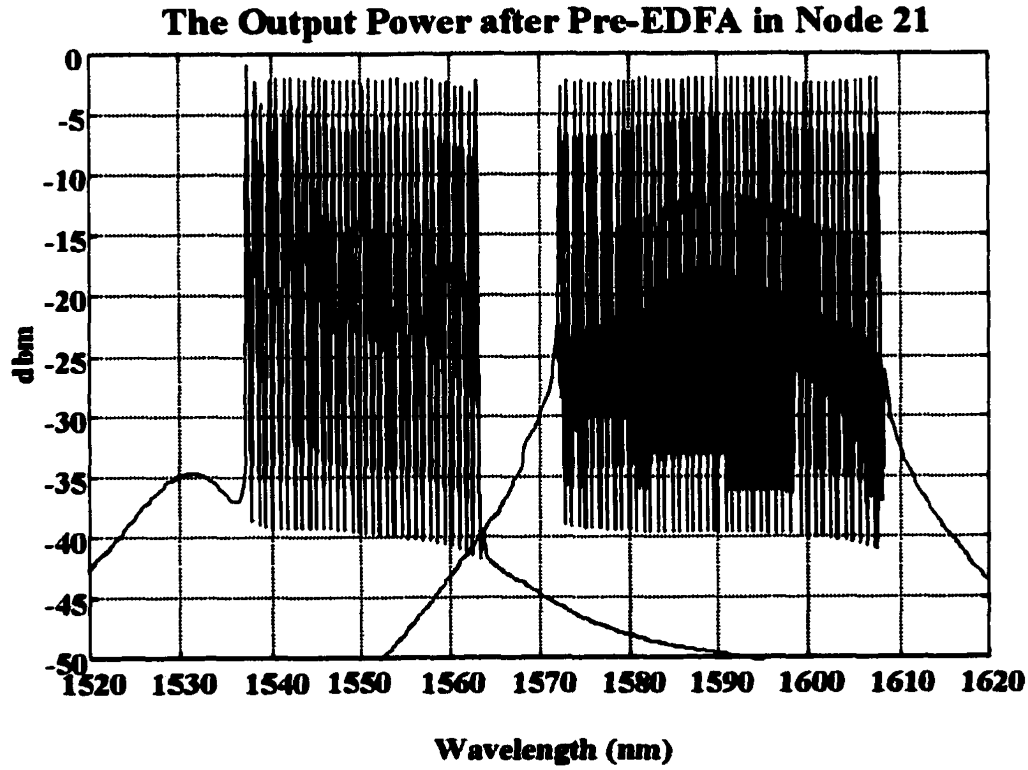


Figure 3-15: The output spectra of node 21.

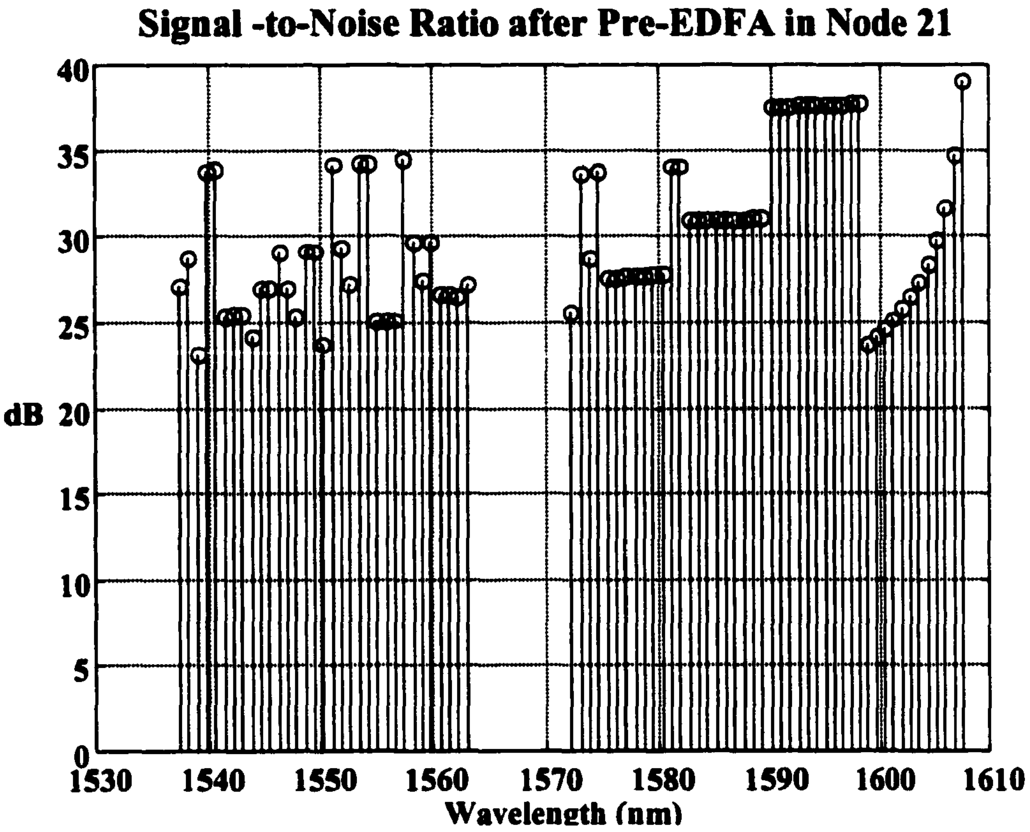


Figure 3-16: The SNR of signals from node 21.

3-6. References

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CHAPTER 4

SURVIVABLE WAVELENGTH-ROUTED WDM NETWORK PLANNING

The network design problem in DWDM-based core transport network can be viewed as a combined two level design problem (see. Figure 4-1), at the bottom level is the design of the physical topology of the optical network, On the top of it is the design of the virtual topologies that are to be supported by this physical topology. These two problems are coupled to each other. The physical topology must ideally be designed with some knowledge about the traffic (light paths) that is supported over it. Likewise, the virtual topology ideally is not designed independent of the physical topology because the physical topology may impose constraints on the set of lightpaths that can be provided to realize the virtual topology.

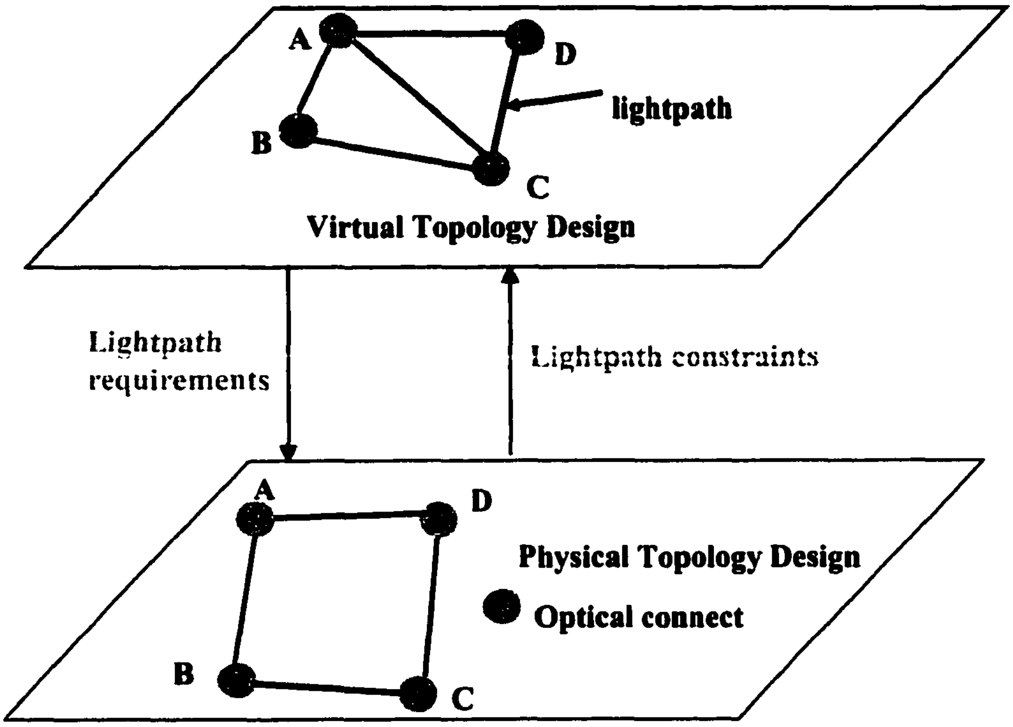

Figure 4-1: The two-level topology design problem

The physical topology of the WDM optical networks employing wavelength routing consists of optical routing nodes, interconnected by pairs of point-to-point fiber links in an arbitrary topology. Lightpaths are setup between nodes on this physical topology. A lightpath is path which is connected the source and sink by a series of fiber links and single wavelength on each of these links will be mapped in that path. For example, in Figure 4-1, node A requires the connection with node C, the path between these two nodes can be either {AB, BC} or {AD, DC}, here each link is assumed to be bi-directional. After one wavelength is mapped on any one of these two possible paths, then one lightpath is setup.

The set of all lightpaths that have been setup between nodes constitute the virtual topology. The nodes of the virtual topology correspond to the nodes of physical topology. The out-degree of a node is the number of transmitters at that node and in-degree is the number of receivers at that node.

For physical topology design problem, the inputs are a general network topology, which will provide the information about how many nodes should be needed, how physical links are to be connected, and also what kind of protection requirements for each connection (fiber layer protection, wavelength layer protection, or our new proposed multi-layer protection). The output of this problem determines the network configuration in terms of the number of fibers, the size of Crossconnects, needed optical amplifiers, add-drop multiplexers, etc. because in most of practical cases, the number of wavelengths per fiber is determined by the technology and is fixed, on the other hand, bundle of fibers are deployed at the same time, multiple fibers on single link can give more savings than using one fiber per link from entire network configuration viewpoint. The factors that affect the cost of network include not only the lightpath cost, but also the cost of "switching" component, in metropolitan area, it may become very significant part of the network cost. The ultimate measure of merit is the cost of network for physical topology design. However, these factors are coupled tightly with the virtual topology design, such as, how many fibers should be needed, what is the size of the crossconnect in each node, etc, are strongly restricted by virtual topology design.

For a given network (topology and resources) and traffic demands, the virtual topology design problem becomes the problem of deciding how lightpaths to set up so as to optimize the performance/cost of the virtual topology. We design the virtual topology that either meets the custom's traffic requirements and minimizes its' cost, or optimize the performance seen by the connections while meeting cost budget. All these also are constraint by the physical topology. The network should also provide different survivability options for working lightpaths, for example, 1:1 protection, 1:N protection, or without protection). These parameters give the constraints for how lightpaths to be routed and wavelengths to be assigned to lightpaths.

How to embed virtual topology to physical topology is routing and wavelength assignment problem, it can be stated as below.

The following inputs are given:

1) A physical topology $G_p=(V,E_p)$, where V is the set of network nodes, and E_p is the set of links connecting the nodes.

2) The maximal number of wavelength channels carried by each link=M. If using multiple fibers, M=nW, n is the number of fiber will be used in each link, W is the number of wavelength can be supported on each fiber.

3) An N x N traffic matrix, where N is the number of network nodes, and the (i, j)th element is the average rate of traffic flow from node i to node j. The traffic flows may be asymmetric.

4) Reliability requirements for each traffic connection.

5) The number of wavelength-tunable lasers and wavelength-tunable (receivers) at each node.

The reason why we use the bounded number of wavelengths is that minimizing the number of wavelengths can result in systems with unrealizable large number of wavelengths, especially the traffic volume is large.[1]

The goal is to determine the following:

1) A Virtual topology (optimal routing), i.e. physical path allocation.

2) A wavelength assignment for lightpaths, wavelength assignment has to satisfy the following two conditions:
    1. Two lightpaths must not be assigned the same wavelength on a given link
    2. If no wavelength conversion is available, the lightpath must be assigned the same wavelength on all the links in its route.

3) The sizes and configuration of the cross-connects at the immediate nodes. Once the virtual topology is determined and the wavelength assignments have been performed, the switch sizes and configurations follow directly.

The Routing and Wavelength Assignment (RWA) problem is closely related to the problem of coloring the nodes in the graph. The optical network can be represented by graph G, where the vertices of graph represent nodes in the network, with an undirected edge between two vertices corresponding to an optical fiber link between the corresponding nodes. To solve RWA problem, it can divide into two sub-problems, first problem is routing problem, i.e. physical path allocation (see goal 1). The second subproblem is wavelength assignment, i.e. assign wavelengths to physical paths according to constraints (see goal (2)), which can be formulated into integer linear program.[2] To solve routing problem according to network survivability requirements, we have to find disjoint-link paths for each source and destination pair. The purpose of finding disjoint link paths is that once the failure occurs on the working path, there always is a disjointed path which can provide protection for the failed working path. There are two different formulations to solve RWA problem, one is the multicommodity flow problem, which considers all possible paths between a source-destination pair. Another is path formulation, which considers a small and fixed number k of shortest paths between any source and destination pair. Because the shorter paths are more likely to be a part of the optimum solution than the longer paths,[3] so the shortest paths are chosen for routing. On the other hand, the shorter path can provide less propagation delay. The flow formulation has been shown that it has N times larger variables and constraints than path formulation, N is the number of nodes in network. It will give the large complexity of solving ILP problem. This will lead that the flow formulation is not scalable to networks with large number of nodes and wavelengths. So in our network planning, the path formulation is chosen.

In order to get link-disjoint paths pair, the shortest path algorithm (Dijkstra's algorithm or Bellmen Ford algorithm) can be used to find the shortest path between each source and destination node pair, then for each source and destination pair, block the shortest path between them, the link disjoint path can be located by using the shortest path algorithm. The first shortest path can be used as primary working path, the second path can be used as protection path. In our method, Dijkstra's algorithm is used to look for the shortest path, it solves the single source shortest-paths problem on a weighted, directed graph G=(V,E), in our application, we assume the cost of each link is 1. Set S contains nodes whose shortest path has been determined. S' is the compensate set of S. pred(s) is the predecessor of node. The following is the Dijkstra's algorithm.

```
begin
  S=0, S'=N;
  d(i)=INFINITY for all node i
  d(s)=0; pred(s)=0
  while |S|<n do
  begin
  let i belonging to S' be a node for which d(i)=min{d(j)|j belongs to S'}
    add i to S; delete i from S'
    for each (i,j) belongs to A(i) do
```

```
            if $d(j)>d(i)+c_{ij}$ then $d(j)=d(i)+c_{ij}$; $pred(j)=i$
        end
    end
end
```

From Dijkstra's algorithm, the nodes except source node are put in S at the increased distance order, and also the algorithm also gives the predecessor information of these nodes, according to information, the shortest paths between source node and all other nodes can be obtained. Therefore, we repeatedly consider each node as source node, then the shortest paths of all node pairs are obtained. This is how we get the first path among four distinct paths for each node pair. However, in order to provide network survivability, the physical paths set must include totally link-disjoint path. Because in mesh network, each node has at least two outgoing links, for each node pair, after the first path is masked, there is still at least one path. However, we are not sure whether the virtue topology is fully connected, so we have to modify our algorithm, at each time, we get the shortest path for only node pair. Repeatedly call the shortest path function, all link-disjoint paths of the first path are got. In fact, this link-disjoint path set is the second path set for four alternative paths set. Using the same principle, and masking one and the part of the rest paths, the rest two distinct paths can be obtained. Up to now, the physical path allocation for each node pair is finished.

We already assume the network topology and traffic matrix (consisting of the number of connections to be established between each node pair) are given, and also the alternate routing table gets computed, then we will formulate the integer linear program according to above information. The Figure 4-2 (a) is the flow chart to formulate the equations. Figure 4-2 (b) shows the flowchart how to solve the RWA problem. First of all, the variables should be well defined, they can indicate the routing and wavelength assignment information after they get solved. The following part shows how to define the variable:

From virtual topology: the variable $V_{i,j}$ =1 if there exists a lightpath from node i to node j into the virtual topology; otherwise $V_{i,j}$ =0;

From Traffic Routing: $\lambda^{sd}_{i,j}$ denotes the traffic routing from node s to node d, and employing $V_{i,j}$ as an intermediate virtual link. Note that traffic from node s to node d may be "bifurcated" with different components taking different sets of lightpaths;

From Physical Topology Route: The variable p^{ij}_{mn}=1 if the fiber link P_{mn} is present in the lightpath for virtual link $V_{i,j}$; p^{ij}_{mn}=0 otherwise;

From wavelength color: the variable c^{ij}_{k}=1if a lightpath from originating node i to terminating node j is assigned the color k.

After the variables get defined, optimality Criterion can be obtained, such as, maximizing total capacity. According to the constraints of virtual topology, traffic Routing, physical topology route, and wavelength continuity. The mathematic model can be built, and all these equations are integer linear programming, and all the variables are binary integers.

We use CPLEX 6.0 software to solve our integer linear programming model, CPLEX is very powerful optimization tool, one option of this software is CPLEX Mixed Integer Solver, and it has the capability to solve problems with mixed integer variables (general or binary). Utilizes state-of-the art algorithms and techniques, including cuts (cliques & covers), heuristics, and a variety of branching and node selection strategies. It includes a sophisticated mixed integer pre-processing system, and solves even large and difficult integer problems quickly and efficiently. So we can embed the CPLEX mixed integer algorithms within our own applications, efficiently and seamlessly.

The output of CPLEX is the variables' values, we already know what each variable stands for, then interpret these values into routing information in each node. Therefore, the switch size can be automatically known from RWA solution.

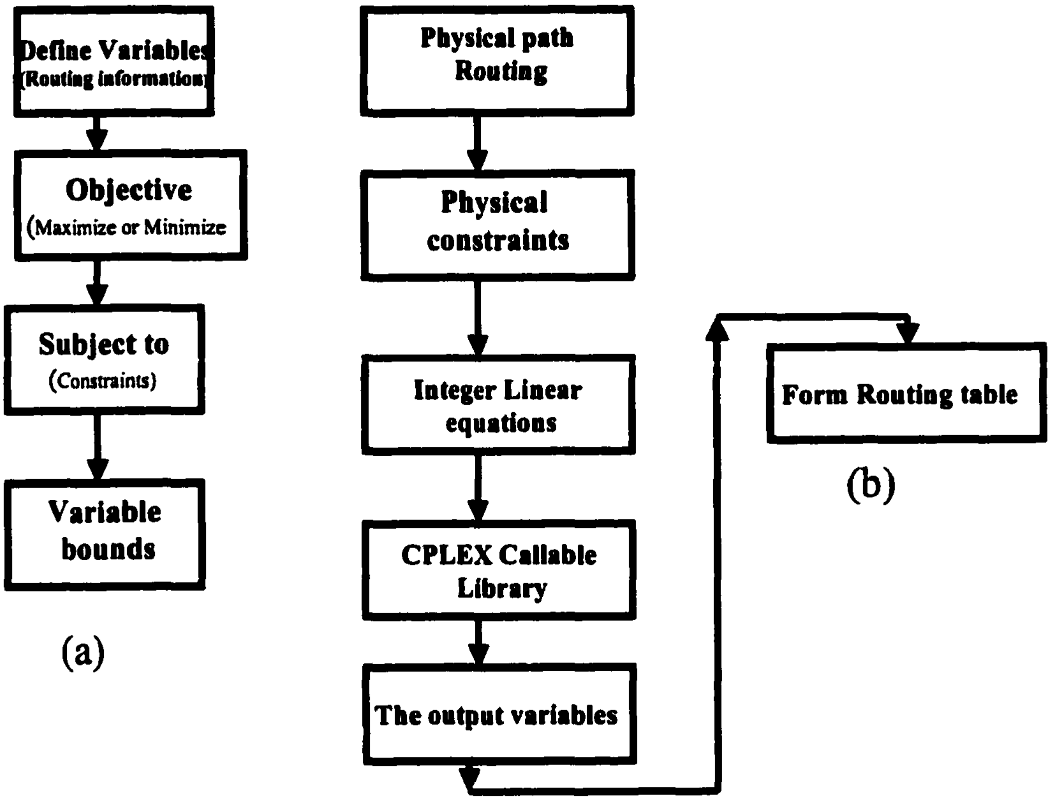

Figure 4-2 (a) Flow chart of how to write integer linear program (b) A view for solving RWA

Of course, after this gets done, the information indicates which links are congested and we can refine our constraints to form new integer linear equations to relieve this congestion and improve its performance. In next chapter, we investigate the application of this design approach in real WDM network.

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CHAPTER 5

ALL OPTICAL PROTECTION/RESTORATION SCHEMES IN DWDM-BASED CORE TRANSPORT NETWORKS

5-1. Introduction

With the unprecedented growth in data traffic and the surging demand for diverse services, ultra-high capacity core transport network facilities are needed. Recent advances in dense wavelength-division multiplexing (DWDM) are expected to provide solutions to this challenge. Communication system suppliers are advertising DWDM transmission systems with capacities greater than 1 T/s over a single fiber by means of multiplexing more than a hundred channels at 10 Gb/s each. As the widespread deployment of such high capacity DWDM systems in the core transport network continues, network survivability becomes a crucial concern. Network survivability, which is the ability of network to recover traffic affected by failures, is becoming a key consideration in the design of broadband telecommunications networks.

Early deployment of DWDM technology has mainly been in a point-to-point manner to increase link bandwidth, supports little in terms of networking functionality and does not yet perform traffic protection or restoration. In cases of fiber cuts or network failures, SONET/SDH equipment would usually provide these functions, with WDM used strictly for fiber capacity expansion. However, recent advances in WDM components and subsystems (WDM add/drop multiplexers (WDM-ADM), optical cross-connects (OXCs)), 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 DWDM technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer.

This chapter presents an overview of existing optical protection/restoration schemes. Then, we present a novel mesh-based hybrid optical protection scheme that utilizes multifiber physical links along with hierarchical OXC structure, which is a combination of fiber cross-connects (FXCs) and wavelength selective cross-connects (WSXC's).

5-2. Network Survivability

Network survivability has been a subject of intense research for quite some time. Even before the WDM technology ushered, network failures have been known to cause severe problems. For example, in November 1988, a fiber-optic cable was severed by construction workers in New Jersey, resulting in 3.5 million call blockages. There are two basic survivability paradigms: protection and restoration. Protection is pre-determined failure recovery, and the protection entity exists as the working entity is established. Here, the protection resources are reserved beforehand, and they may be used by low priority traffic if traffic pre-emption is allowed. Restoration dynamically discovers the alternate route from spare resources in network for disrupted traffic once the failure is detected. If no new route is discovered for a broken working path, data carried by that working path would be lost. Because the backup capacity is not reserved beforehand and it is always available to other traffic, restoration schemes have better resource utilization than protection schemes. However, restoration schemes require longer restoration time because they need to compute the backup path after failure detection and the backup path is established by using some kind of signaling mechanism. All these steps take time to complete. Therefore, restoration schemes are not good for guaranteeing survivability to mission critical connections or applications. In the following section, we will give the overview of the conventional optical protection /restoration schemes.

5-3. An Overview of Optical Protection/Restoration Schemes

The emergence of survivable WDM optical network architectures will likely mirror the emergence of SONET/SDH survivable architectures. Both SONET/SDH and WDM optical survivable architectures have been classified as either protection or restoration architectures.[1-4] The advantages of using all-optical protection are that: (1) the network can achieve the transparency at bit rate and format; (2) the network architecture will be simpler. But the optical protection only can protect facility failure. When the equipment failure happens, the optical protection can isolate this failure equipment out and keep the rest of the network working. In section 5.3.1, the classes of protection architecture are described.

5-3-1. Overview of Classes of Protection Architectures

Protection of the elements that support transmission in the network comes in two flavors: equipment protection and facility protection. The level of survivability provided for a particular facility often depends upon a combination of both the type equipment protection and the type of facility protection provided.

5-3-1-1. Equipment Protection

Equipment protection is supported by providing spare equipment – often referred to as a “hot-standby” or “protection” equipment – for 1 (known as 1:1 equipment protection) or more (known as 1:N equipment protection, N>1) instances of in-service (“working”) equipment. For example, a stand-by transmitter may be provided for each working transmitter (1:1 equipment protection), or a spare transmitter may be shared by among three transmitters (1:3 equipment protection) in a fiber optical terminal. In general, equipment protection can be M: N, when M protection entities are shared among N working entities.

5-3-1-2. Facility Protection

Facility protection can be classified as either 1+1, where every working facility has a dedicated protection facility, or M:N, where M protection entities are shared among N working entities. In general, facility protection switching involves bridging a signal onto a protection facility at the transmit end, and switching from the failed facility to the protection facility at the receive end. Depending upon the facility protection architecture, the "bridge" may refer to either (1) a coupling or broadcast of the signal on to both the working and protection facilities at the transmit end, or (2) a switch from one facility to the other at the transmit end.

5-3-1-2-1. 1+1 Facility Protection

In 1+1 facility protection, a spare (protection) facility is provided for every in-service (working) facility, and the traffic is permanently bridged to both the working and protection facilities at the transmit end. Since the signal is permanently bridged at the transmit end, 1+1 protection switching involves only a switch at the receive end, where one of the two received signal is selected. The level of survivability provided by this architecture depends on whether equipment protection is provided.

In 1+1 optical facility protection, service is protected only from link failures using an optical splitter to bridge the optical signal on the diversely routed working and protection facilities. In the event of a single link failure, an optical switch at receive end switch to the alternate facility. This is referred to as 1+1 optical facility protection as only the link is protected (protection switching takes place in the optical domain). A Tx or Rx failure will lead to loss of service, unless the Tx/Rx are independently protected. The difference between 1+1 optical facility protection and 1+1 electrical facility protection is subtle, in 1+1 electrical facility protection, service is protected from both link failures (e.g., fiber cuts) and equipment (Tx/Rx) failures using duplicated Tx/Rx pairs over diversely routed facilities. Both incoming signals are detected and can be continuously compared in order to select the better of the two. In 1+1 optical facility protection, with only one Rx at the receive end, a failure of the incoming signal will be detected at the Rx, and a "blind switch" will occur, i.e., the selector will switch to the alternate facility without knowledge of the quality of the signal on that facility. The 1+1 architectures are considered dedicated protection architectures, as the protection capacity (i.e., protection facility, and protection electronic, if provided) is dedicated to the working capacity and cannot be used for any other purpose (e.g., for extra traffic-low priority unprotected circuits), even in the absence of a failure.

5-3-1-2-2. 1:1 Facility Protection

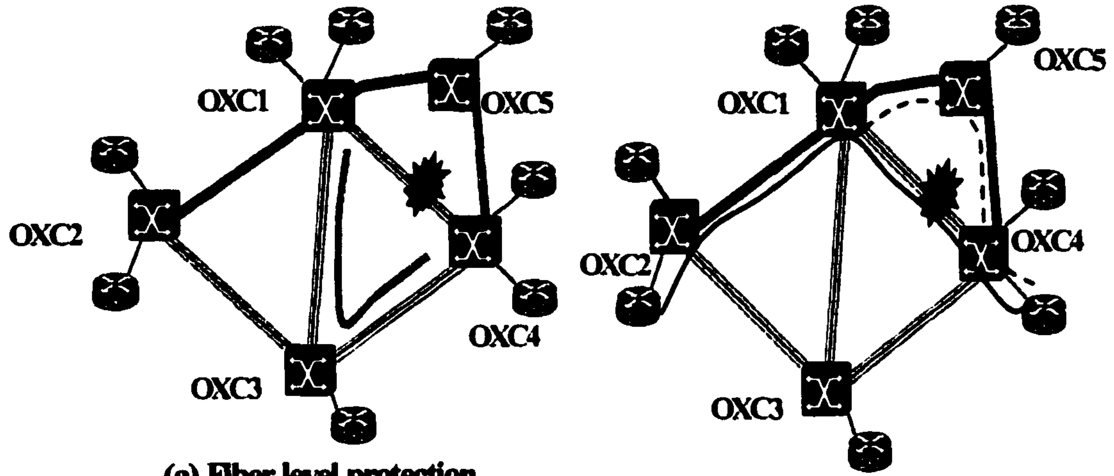
The 1:1 optical facility protection architecture is similar to 1+1 optical facility protection in that diversely routed facilities protect against link failures. The difference between 1+1 and 1:1 optical facility protection is that in 1:1, the service is not permanently bridged to both the working and protection facilities. In 1:1 optical facility protection, service is carried only on the working facility – the protection facility is used only in the event of a failure. An APS channel is required to coordinate a protection switch in the event of a fiber cut. In 1:1 electrical facility protection, a spared Tx/Rx that are in constant communication over the protection facility can support an APS channel. In 1:1 optical facility protection, no communication path exists over the protection facility until the transmit end bridges the signal to the protection facility and the receive end switches to the protection facility to receive that signal. In this case, in the event of a failure in which both working fibers are cut, no APS communications path exists between the endpoints, i.e., each end detecting a failure will try to send a bridge request message to the transmit end, but will receive no response. To determine if the transmit end has actually performed the bridge, the receive end will have to do a blind (i.e., uncoordinated) switch to the protection facility, and only then can the receive end determine that either (1) the bridge has been performed and all is well, or (2) the protection fiber has also been cut, or the transmit end failed to bridge the signal to protection. As such, another means of supporting an APS channel will have to be developed for the 1:1 optical facility protection architecture. Note that while this is a 1:1 architecture, no extra traffic can be supported, as this architecture lacks the spare transmitters and receivers necessary to support transmission and reception of extra traffic over the protection facility.

5-3-1-3. 1:N Facility Protection

Similar to 1:1 facility protection, in 1:N facility protection N working entities share one protection entity. In 1:N the APS message from the receive end requesting a bridge must indicate to the transmit end which of the N working facilities should be bridged to the protection facility. In the case of simultaneous failures, contention for the protection facility results, which is resolved in SONET 1:N linear APS using the working channel number requesting protection (i.e., working facility number 1-N) and its associated priority.

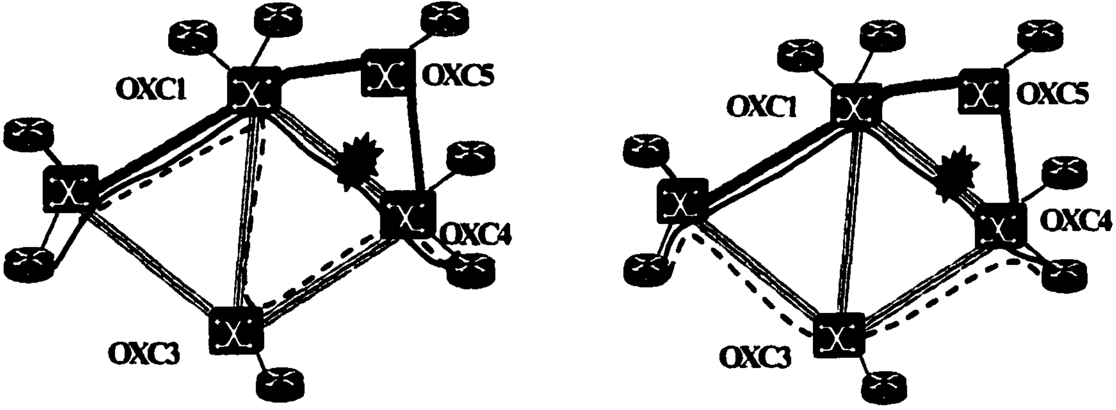
5-3-2. Optical Protection Schemes

There are two main protection schemes in optical domain: the fiber-based protection scheme and the channel level protection (as shown in Figure 5-1).



(a) Fiber level protection

(b) Channel level link protection



(c) Channel level path protection

(d) Channel level disjoint path protection

Figure 5-1: Optical protection schemes in fiber level and channel level respectively

5-3-2-1. Fiber (OMS) Level Protection Scheme

The fiber-based protection is employed at the optical multiplex section (OMS) level by performing fiber protection switching (Figure 5-1(a)). Assume there is fiber cut between OXC1 and OXC4, after failure detection, OXC1 switches the traffic to the protection fiber between OXC1 and OXC3, then the restored traffic will bypass OXC3 and continue to transmit in the protection fiber between OXC3 and OXC4, finally route back to the normal status. The protection granularity is one fiber capacity. Its applications include linear (point-to-point) and ring architectures. Each working fiber is backed by another disjointed protection fiber path in the ring, e.g. automatic protection switching (APS). This fiber-based protection scheme only requires simple control and management mechanisms, and provides sub-50ms protection speeds, which is the benchmark established by SONET rings. However, beyond providing simple fast traffic restoration, the network utilization is also very important. A major drawback of fiber-based protection is its very low network utilization.

5-3-2-2. Optical Channel Protection Scheme

Optical channel level protection scheme's applications primarily involve cross-connect-based mesh architectures, which is slower but more bandwidth efficient. This scheme is deployed at the optical channel (OCh) level (i.e. the wavelength level). While this channel protection scheme is similar to the higher layer protection, it includes three variants.

Link protection, which reroutes the disrupted traffic between the end nodes of the failed link (shown in Figure 5-1(b)). This approach offers the fastest failure detection and tries to recover traffic locally at the expense of efficiency (more hops, more bandwidth, more end-to-end delay).[5-6]

Path protection, which reroutes the broken traffic between the two end nodes of the affected path (shown in Figure 5-1(c)), and takes full advantage of the spare capacity all over the network. It has lower spare capacity requirement (as expected) than link protection, but it takes longer time to detect failure, propagate the error notification to source node and set up the alternate path.

Disjoint-link path protection which is a special case of path protection (shown in Figure 5-1(d)). This technique adds the link-disjoint constraint to path selection, and can restore traffic immediately once it discovers the path failure. It doesn't need to know the exact location of the failure, so it is capable of protecting against multiple simultaneous failures on the working lightpath.

5-4. A Novel Mesh-based Hybrid Optical Protection Scheme

5-4-1. The Basic Principle of HPS

In this section, we propose a mesh-based hybrid OMS/OCh protection scheme that utilizes multifiber physical links along with hierarchical OXC structure, which is a combination of fiber cross-connects (FXCs) and wavelength selective cross-connects (WSXC's). FXCs connect fibers without MUX/DMUX module and without WSXCs/WIXCs. FXC operates at the fiber level whereas WSXC/WIXC operates at the wavelength level. Here, FXC is employed for protection purposes against failures, and WSXC/WIXC is used for channel provisioning. As the traffic volume increases, more and more fibers will go through the network nodes via an express (pass-through) node without adding or dropping any wavelengths. Karasan *et al*[7] have proposed a multilayer OXC architecture for working traffic. It is claimed that significant cost reductions can be achieved by dividing the functionality of the OXC between FXC and WSXC/WIXC. However, there is still no published work on how to design, simulate, separate various tasks (e.g., protection/restoration) among various layers, and operate these networks. The hybrid protection scheme proposed here addresses these issues.

In a hybrid protection scheme (HPS), each wavelength/each fiber is packed according to reliability property of each fiber/each wavelength assigned, i.e., we use grooming to pack data flows into wavelengths before traffic gets into the optical domain, and at the edge OXC, reasonably distribute wavelengths into different fibers. For the compacted fiber, which contains the largest number of working wavelengths, the fiber level protection is adopted. For the sparsely packed fiber, the OCh level protection is used. Compared with the other two single level optical protection schemes, HPS is expected to lower the cost (including operational and capital costs), provide more flexible protection options, medium computational complexity, and acceptable network utilization (see Table 1).[8]

Table 1: Comparison of three different layer protection schemes

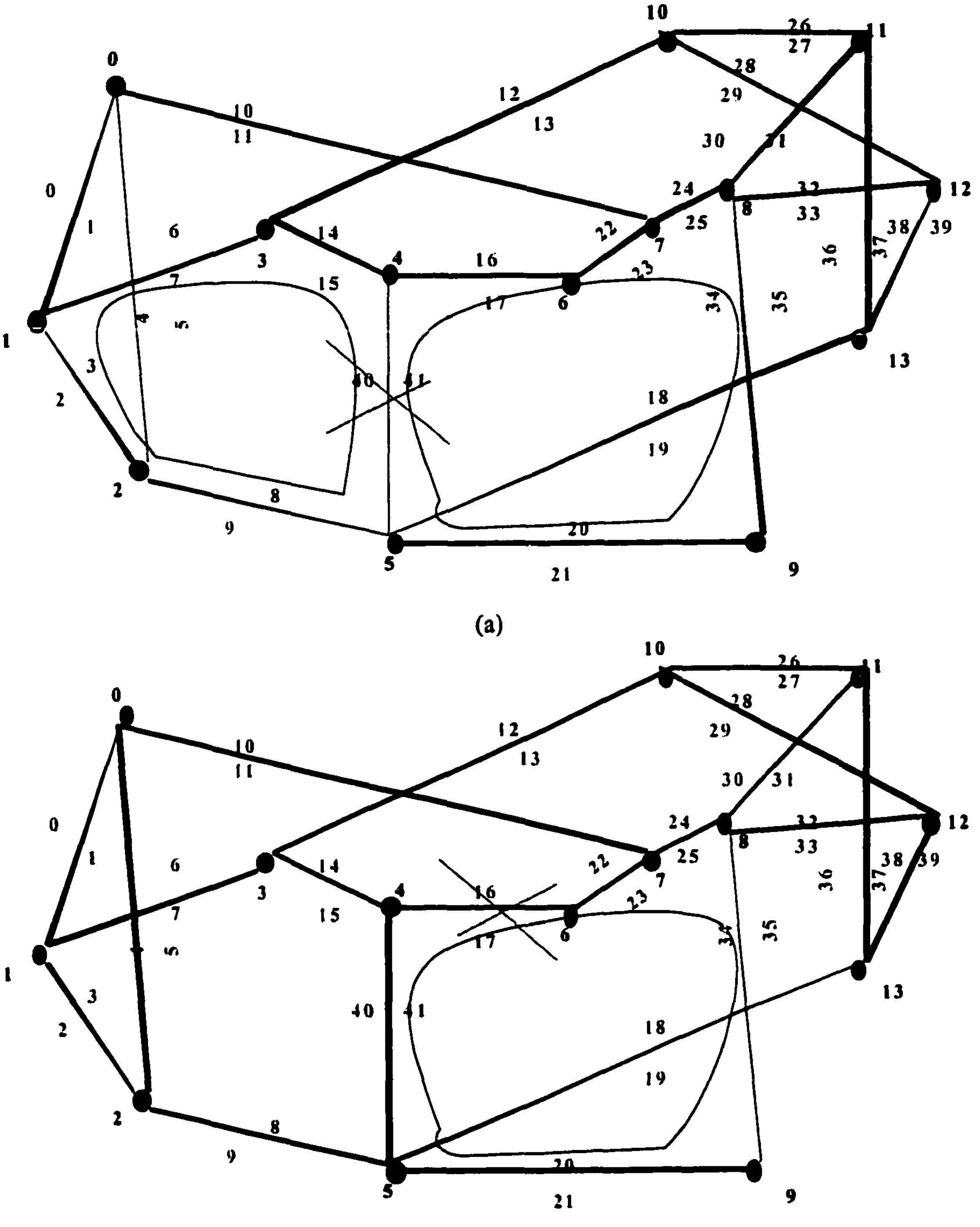
	Network utilization	Computation complexity	cost	Design Flexibility
Fiber layer scheme	Low	Low	High	Very low
Wavelength layer scheme	High	High	Very high	Flexible
Hybrid protection scheme	Medium	Medium	Low	Very Flexible

The proposed HPS can provide four different reliability options for individual connections: OMS protection, OCh level path protection, OCh level link protection, and best effort failure recovery. OMS protection can offer the fastest and most reliable connection. OCh level path/link protection requires longer switching time than OMS protection. If OXC configuration time is relatively fast (10 μs), OCh level path protection takes longer protection switching time than OCh level link protection. If OXC configuration time is slow (500 μs), the average protection switching time of OCh level link protection is longer than that of path protection.[6] Some connections may not require any protection, in which case the recovery can be implemented through either restoration in optical domain or protection/restoration at a higher layer. This cannot guarantee 100%

survivability. Depending on the reliability requirement, the connections are groomed into working fibers provisioned with different priorities. Each fiber in the link is assigned different priority since we only have one spare fiber per link, and for a given physical directional link, if there is unprotected working fiber, the protection for this fiber is realized by OCh level protection or best effort failure recovery. Each wavelength inside the unprotected fiber is also given different priority. The traffic-grooming rule in optical domain is such that a highly reliable connection cannot be assigned to a less reliable wavelength, but a less reliable connection can be assigned to a highly reliable wavelength. The traffic is packed, as tightly as possible, into the working fiber with loop protection.

The mesh-based HPS takes advantage of the basic characteristic of a mesh-based network, which is the edge redundancy. The edge redundancy means that for each node there are at least two physical connections with other nodes in the network. Therefore, any lightpath (between source and destination) always has some alternative paths in the network, and for each physical link (physical connection between two adjacent nodes), there exists at least one loop which covers that link. A physical link may be covered by multiple loops. Note that a lightpath is defined here as an all-optical channel, which may span multiple fiber links to connect a source node with a destination node. There is no wavelength converter in the targeted network. Therefore, the lightpath must keep the same wavelength from one end to the other. Nevertheless, we assume wavelength agility in the terminals, which means that the protection path may have a different wavelength than that of the working path. According to this unique property of a mesh-based network, the HPS works as follows: each link is assigned a spare fiber to provide WDM loop-back recovery against physical link/component failure. It can also be used to transmit low priority traffic in normal network conditions. The traffic carried by spare fibers passes through neither DMUX/MUX nor switching units. A spare fiber directly connects to an additional NxN FXC, where N is the number of fibers connected to a given node. Thus, the number of wavelengths going through WSXCs or WIXCs can be significantly reduced, which leads to the reduction of both operational and hardware cost.

We assess the performance for such hybrid protection scheme via simulation of the mesh-based NSFNET. The NSFNET, Figure 5-2, consists of 14 nodes. Each adjacent node pair is connected through two directional physical links (in opposite directions, to allow bi-directional traffic flow between the two adjacent nosed). Each physical directional link consists of at most two working fibers and one spare fiber in the same direction as the working fibers. For example, in our study case, link 40 carries traffic from node 4 to node 5 and consists of three fibers, and link 41 carries traffic from node 5 to 4 and also consists of three fibers, but in opposite direction. The total number of directional links is 42. The traffic load is almost evenly allocated over source-destination pairs, and the total number of lightpaths is 350. Most source-destination pairs have a higher demand than 1.



(a)

(b)

Figure 5-2: 14 node NSFNET mesh network topology. (a) Multiple loop protection in HPS. (b) Fiber loop protection cannot provide full survivability since no multiple loops which only share with the failed link exist. The channel level protection has to coordinate with fiber level protection to achieve 100% protection.

Two major steps are carried out to simulate the NSFNET: (I) network configuration, and (II) developing a heuristic algorithm (based on the shortest path algorithm) to calculate all possible recovery loops.

I. **Network Configuration**: We use three sub-steps in network configuration. First, we optimize routing and wavelength assignment (RWA) together with their capacities and network traffic loads. The RWA problem can be formulated as an ILP problem where our objective is to minimize the total capacity for a given traffic pattern. We assume that each fiber carries 16 wavelengths. Second, the working paths are groomed according to the priority rule described earlier. Finally, the spare capacity is assigned by using OCh path protection or link protection. In our simulations, we require 100% protection at the optical layer.

II. **Calculating Recovery Loops**: We develop a heuristic algorithm (based on graph theory) to calculate loops. First, we remove the edge which represents the failed cable link in the graph, and use the shortest path algorithm (Dijkstra's algorithm) to find another route which connects the two end nodes of the failed cable link. This route and the failed cable link consist of only one complete recovery loop. Thus, the route for fiber protection is found. Second, if there are multiple loops which cover that failed cable link, we remove the known loops from the graph, use the shortest path algorithm again to look for the next available possible route, which connect the two end nodes. Finally, the second step is repeated till all the other possible qualified loops have been located.

5-4-2. The ILP Formulation for Working Capacity Assignment

In this section, we develop ILP formulation for any multifiber network to assign working path capacity. We precompute a set of alternate routes for each source-destination (s-d) pair by using *kth* shortest path algorithm, in our study case, $k \leq 4$. We make sure that there is a disjointed link path in alternate routes for each path. Our objective is to minimize the total capacity for the certain traffic pattern. Each fiber has ability to carry W wavelengths, $W=16$. We assume the following conditions are given: 1) the network topology can be represented as the directed graph, the link in the graph are numbered 1 through E; 2) the traffic demands are known, i.e. the number of requests for each s-d pair are given. In our notation, d_i stands for the traffic demands of the *ith* s-d pair in a demand matrix, s-d pairs are numbered from *1* to *N(N-1)*; 3) the alternate routes R^i are already precomputed. The ILPs show the relationship among the following variables:

m: the number of working fibers per link, in our case, $m=2$.

W_j : the number of wavelengths used by working path on link *j*.

$r_w^{i,r} \leq m$ if the k^{th} route between node-pair i utilizes wavelength *w*, the variable equals to 1, otherwise it equals to 0.

The ILP formulation consists of the objective, constraints and bounds. CPLEX6.0 is used to solve these equations, since the number of variables is more than the number of constraints and bounds, the equations may have more than one solution. Fortunately CPLEX helps us get the optimal solution.

The objective of our working path assignment is to minimize the total capacity used:

$$Minimize \sum_{j=1}^{E} W_j$$

The following equations belong to constraint part:

The number of lightpath between each s-d pair satisfies the traffic demands:

$$d_i = \sum_{k=1}^{M} \sum_{w=1}^{W} r_w^{i,k} \qquad 1 \le i \le N(N-1)$$

The number of working lightpaths traversing link *j*:

$$W_j = \sum_{i=1}^{N(N-1)} \sum_{k \in R^i, j \in k} \sum_{w=1}^{W} r_w^{i,k} \qquad 1 \le j \le E$$

In our network, we don't consider wavelength conversion, therefore, the lightpath must keep wavelength-continuity for end-end transmission, since we use *m* fibers per link, and the following constraints must be satisfied:

$$\sum_{i=i}^{N(N-1)} \sum_{k \in R^i, j \in k} r_w^{i,k} \le m \qquad 1 \le w \le W,\ 1 \le j \le E$$

The bounds in ILP are the value range of variables.

5-4-3. A Case Study

We show two different important protection cases that can be provided by the HPS. The first case represents the situation where the loop recovery alone (at the OMS level) can totally restore all disrupted traffic (100% protection is assumed at the optical layer). We simulate this case by cutting the cables between nodes 4 and 5. Note that this cable carries a total of six fibers; three are allocated to the outgoing physical link (link # 40) from node 4-to-5; the other three are allocated to the outgoing physical link (link # 41) from node 5-to-4. As shown in Fig. 4-2(a), all traffic passing through links 41 and 40 can be totally restored by two physical loops, loop 1 and loop 2, respectively. Loop 1 consists of nodes 4, 5, 2, 1, 3, 4; loop 2 consists of nodes 4, 6, 7, 8, 9, 5, 4. Thus, the HPS can provide 100% protection using multiple loop protection alone at the OMS level.

The second case represents the situation where the loop recovery alone (at the OMS level) cannot totally restore all disrupted traffic. In this case, the rest of the disrupted connections will be protected by the OCh protection level through the alternate paths in other working fibers in the whole network. Note that for those failed cable links which connect a pair of adjacent nodes such that one of these nodes has only two outgoing edges, the loop recovery cannot totally restore all disrupted traffic. In the NSFNET, the links, which connect node 6 or 9, fall in this category. We simulate this case by cutting the cable between nodes 4 and 6, as an illustrative example, to demonstrate how the hybrid protection scheme handles this case without the loss of generality. In this case, the traffic passing through links 16 (from node 4 to node 6) and 17 (from node 6 to node 4) gets disrupted. Table 2 (a) shows the status of wavelength utilization in each working fiber at links 16 and 17 before the cable link is cut. In this table, 1 means the wavelength is used, 0 means the wavelength isn't used. The traffic passing through fiber 16b is restored by fiber protection (shown in Figure 5-2(b)), with 3 connections still left for the OCh protection in fiber 16a. As to link 17, after fiber 17a has used the same physical loop but in different direction to provide protection, there still remain 3 connections in fiber 17b. Table 2 (b) shows how OCh protection scheme provides protection for these remaining connections. As shown in Table 2 (b), the wavelength agility is allowed in the HPS. For example, for working path from node 10 to node 6, it passes through links 13, 14, 16 by using λ_0 , and the link-disjointed protection path goes through links 28, 33, 25, 23 by using λ_{11}.

Wavelength	link 16		link 17	
	fiber (a)	fiber (b)	fiber(a)	fiber(b)
0	1	1	1	1
1	0	1	1	0
2	1	1	1	1
3	0	1	0	0
4	0	1	1	1
5	0	0	1	0
6	0	1	0	0
7	0	1	0	0
8	1	1	1	0
9	0	1	0	0
10	0	1	1	0
11	0	1	1	0
12	0	1	1	0
13	0	1	0	0
14	0	1	1	0
15	0	1	1	0

(a)

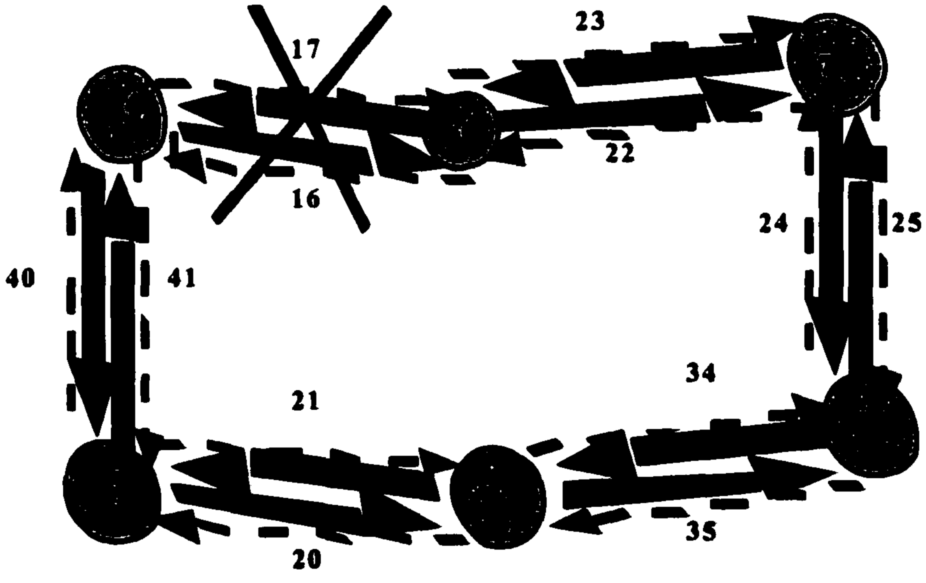
Working path {s,d}	Protection path	Wavelength needed to be protected in working path	Wavelength in protection path
16 {4, 6}	15, 7, 1, 10, 23	λ_2	λ_1
16, 22, 24 {4, 8}	40, 20, 35	λ_8	λ_8
13,14,16 {10, 6}	28, 33, 25,23	λ_0	λ_{11}
17, 40 {6,5}	22,11,4,8	λ_0	λ_7
23, 17 {7, 4}	11, 0, 6, 14	λ_4	λ_6
17, 15, 12 {6,10}	22, 24, 30, 27	λ_2	λ_7

(b)

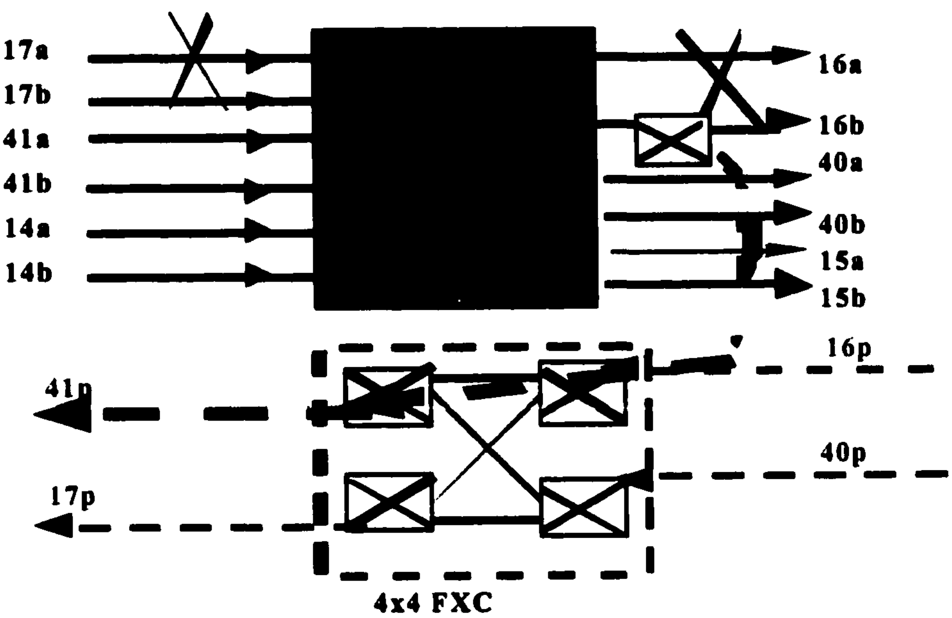
Table 2: (a) The wavelength utilization status of links 16 and 17. Fibers 16b, and 17a are selected as protection fibers. (b) Routes and wavelengths of working paths and protection paths for channel protection.

Next, for the same traffic load, we compare the working and capacity assignment for the pure shared path OCh protection with the HPS scheme. The shared path channel protection has been shown to provide significant savings in capacity utilization over other channel level protection schemes.[5] In shared path protection, the number of variables is doubled in ILP since the protection paths are also considered. Simulation results have shown that HPS saves up to 20% channel ports inside OXC while network utilization decreases from 54% to 50%.[8] In HPS, OCh protection paths share the same hardware as the working paths. But for fiber protection, we need to add FXC at each node.

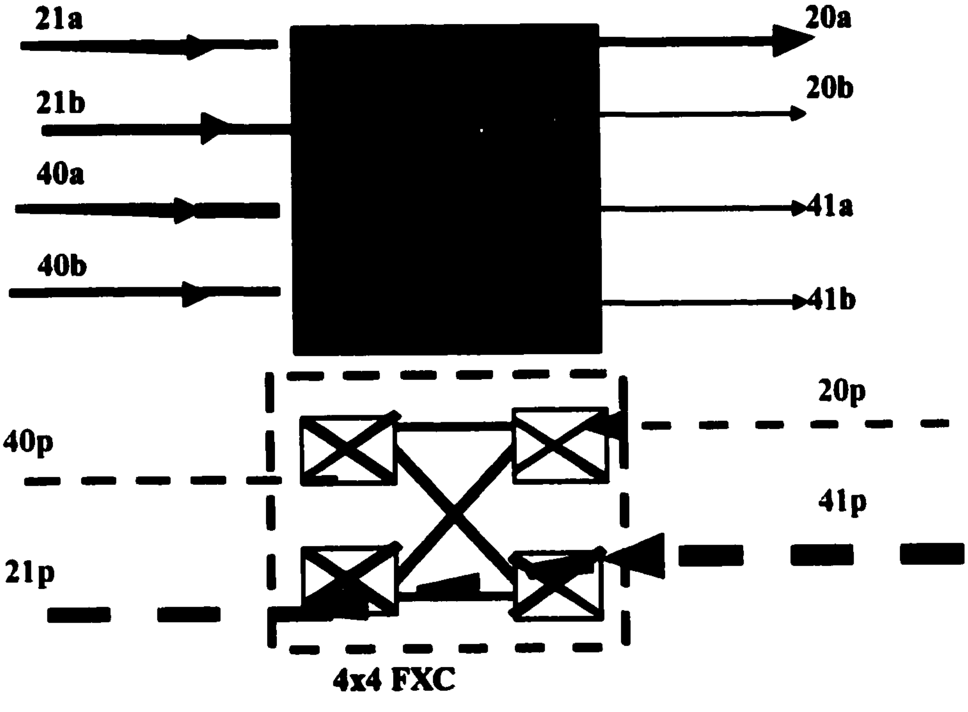
The switch fabrics for the proposed HPS are shown in Figs. 5-3 (b), (c), and (d). When compared with the conventional WSXC/WIXC, the additional fully connected 4×4 fiber protection switch and several 2×2 switches at the input/output of the working fibers are added. In Figure 5-3 (a), we only show those components, which are relevant in restoring traffic passing through fiber 16b. In node 4, the traffic passing through fiber 16b before the cable cut will directly switch to 4×4 fiber protection switch through 2×2 switch (shown in Figure 5-3 (b)). In the bypassing nodes in the protection loop, such as nodes 5, 9, 8, 7, only fiber protection switch works for routing the protection traffic. In the looping back (e.g., 6 in Figure 5-3 (d)), 4×4 fiber protection switch will direct the traffic back to WSXC. These additional 4×4 and 2×2 non-block switches can be integrated into the WSXC, which employs silica-based planar lightwave circuits (PLCs).[9]



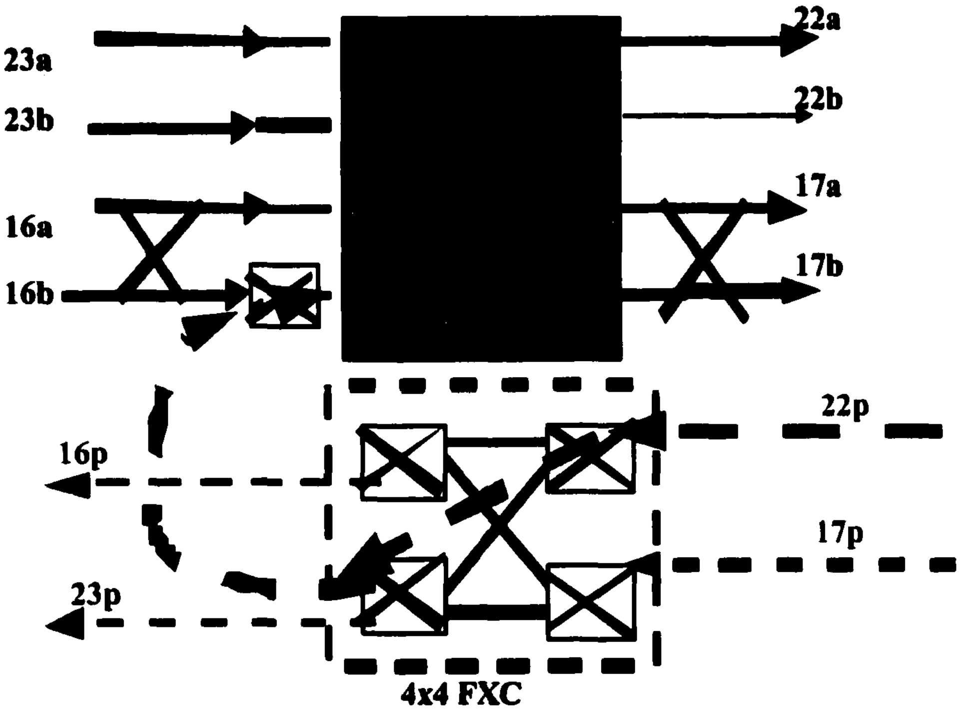
(a)


17a
17b
41a
41b
14a
14b
16a
16b
40a
40b
15a
15b
16p
41p
40p
17p
4x4 FXC

(b)


21a
21b
40a
40b
20a
20b
41a
41b
20p
40p
41p
21p
4x4 FXC

(c)



(d)

Figure 5-3: (a) Demonstration of fibers cut between Node 4 and Node 6 in hybrid protection WDM network, the thick line represents 2 working fibers. Dashline in each link is one protection fiber. (b) For Node 4, all the traffic from fiber 16b switch to the protection fiber of link 41 through FXC. (c) shows how restored traffic pass through the bypassing node in thick dash line (Node 5 is shown). (d) shows how the restored traffic loops back to Node 6 through 4×4 FXC and 2×2 switches.

5-5. Conclusion

In this chapter, we have introduced a novel mesh-based hybrid protection scheme that utilizes a combination of FXCs and WSXCs. The ILPs formulation has been developed for the optimal solution of working capacity assignment for any topology. The simulation results have shown that HPS saves up to 20% channel ports inside OXC, and network utilization of HPS only degrades from 54% down to 50%. Through our analysis, we conclude that this hybrid protection scheme is capable of reducing overall network cost and computation complexity, providing more reliability options for network operator, achieving good network utilization, and realizing simple network management mechanism. Finally, we have described the hardware implementation HPS.

5-6. References

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CHAPTER 6

JOINT PROTECTION/RESTORATION IN IP-CENTRIC DWDM-BASED OPTICAL TRANSPORT NETWORKS

6-1. Introduction

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 (shown in Figure 6-1).

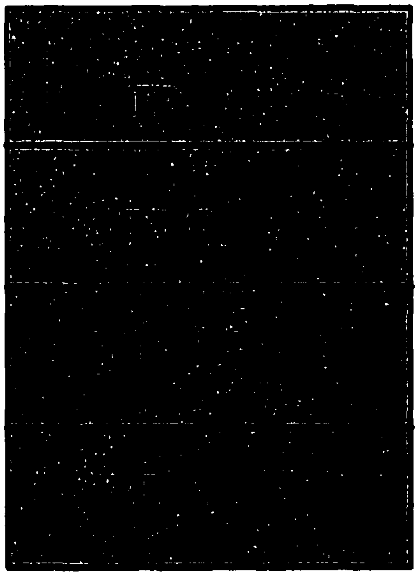


Figure 6-1: today's core network architecture model

This approach has functional overlap among its layers, contains outdated functionality, and is too slow to scale, which make it ineffective as the architecture for the envisioned next generation optical data networks. An important and challenging consideration in such multilayer transport networks is the inter-working of optical survivable architectures with existing similar survivability schemes that are already available at the higher layers. The major challenges are to determine which layer(s) is responsible for each failure (recovery approach), to establish a strategy to coordinate single-layer recovery actions (escalation strategy). These strategies are critical to the integration of WDM technology into telecommunications networks.

This chapter examines how to allocate protection/restoration functionality between the optical layer and the data layer. A central issue for the successful implementation of this approach is the reduction of the cost and complexity associated with today's multi-layer core transport network architecture. This may be achieved through the elimination of unnecessary network layers, to avoid functional overlap and wasteful duplication, among today's conventional four-layers core transport network model. In this view of reduced or "collapsed" network layers, this chapter examines the notion of supporting "data directly over optics", where existing TDM systems (e.g., SONET/SDH) play a diminishing role, and Optical Transport Networking emerges as the underlying transport infrastructure for the envisioned "DWDM-based IP-centric optical Internet". To address the limitations of the multi-layering approach, this work presents an overview of a more direct IP standards-based approach for closer and efficient IP-WDM integration. This approach combines recent advances in IP multiprotocol label switching (MPLS) traffic engineering control plane constructs with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks. Finally, having established the notion of mapping IP directly onto the WDM layer, we present and develop a simple and integrated hybrid protection/restoration scheme that can be coordinated at both the IP and WDM layers.

6-2. The Vision of an IP-Centric DWDM-Based Optical Data Networking Paradigm

6-2-1. Introduction

If predictions of exponential growth in Internet-related traffic over the next decade hold true, a network 100 times the size of today's voice network will be needed-with voice relegated to a 1 percent minority share of a 99 percent data-dominated network. What kind of technology can best meet these demands to deliver such a "network of networks"; take the most widely talked about data networking protocol-IP-and combine it with the ultimate in bandwidth provisioning-DWDM-to realize the ultimate "blend" of hot technologies. The vision of a hybrid IP-centric optical Internet have captured the imagination of researcher and network planners alike since the rapid and successful commercialization of DWDM in the early-mid 1990s. Such a network will take advantage of the massive raw bandwidth afforded by dense wavelength division multiplexing (DWDM) in its core. Communication system suppliers are advertising DWDM transmission systems with capacities greater than 1 T/s over a single fiber by means of multiplexing more than a hundred channels at 10 Gb/s each. Much of this capacity growth has been in point-to-point long-distance backbone transmission. While DWDM promises to scale sufficiently in capacity to meet the exponential growth in bandwidth demand, is simply a "dumb" fiber-multiplier. Harnessing the raw bandwidth that DWDM delivers into manageable services that can meet the exponential growth in network traffic is the new real challenge. On the other hand, although present IP networks offer flexibility and scalability, they do not have the capability to support traffic-engineering. Traffic-engineering is a loose term that encompasses many aspects of network performance. These include the provision of a guaranteed quality of service (QoS), improving the utilization of network resources by spreading traffic evenly in the network, and providing features for quick recovery when a node or link fails.

Today's core network architecture model has functional overlap among its layers, contains outdated functionality, and is too slow to scale, which make it ineffective as the architecture for the envisioned optical data "network of networks". The notion of supporting "data directly over optics" has been fueled by the promise that elimination of unnecessary network layers will lead to a vast reduction in the cost and complexity of the network. In this view of reduced or "collapsed" network layers, existing TDM systems (e.g., SONET/SDH) play a diminishing role, and Optical Transport Networking emerges as the underlying transport infrastructure for the resultant "network of networks". Although early deployment of DWDM technology has mainly been in a point-to-point manner to increase link bandwidth, improvements in components and subsystems are now beginning to shift the focus more towards network-level issues. Increasingly, network layer "electronic" switching is becoming the bottleneck as opposed to link bandwidth, and the trend is towards simpler, faster core networks. As a result, the efficient internetworking of higher layer protocols, most notably IP, over WDM networks is a primary concern.

For closer integration with higher-layer networking protocols, most notably IP, an optical control framework is necessary. Specifically, scalable protocols are required to handle the increasing network complexities/dimensionalities and interact with IP routing and traffic/policy management protocols. Much of the current work in this area has essentially focused on defining a lower (access) protocol layer for WDM networks to provide "circuit-switched" services to multiple higher-layer protocols (IP, ATM), i.e., optical-layering approach.[1-6] This layer "optical adaptation layer" will perform channel routing, maintenance, and likely even restoration/protection tasks. In view of this layering approach, the WDM network is treated as a separate network layer and interfaces are provided for higher-layer "client" protocols to request "circuit-switched" lightpath channels. Typical lightpath channels are of large bandwidth granularity, ranging from OC-48 to OC-192 and even OC-768. For IP integration, this approach allows for a more direct "two-layer" integration (i.e., IP-over-WDM) and is an improvement over the current three/four layer schemes (i.e., IP-ATM-SONET-WDM or IP-SONET-WDM.[6] An advantage here is that multiple protocols can be supported, i.e., multi-protocol insensitivity. However, as more services migrate towards IP transport, such protocol "transparency" may be less of a concern. Additionally, akin to issues in IP-over-ATM case, the optical-layering approach will inevitably introduce additional integration complexity, increases operations costs and poses inter-operability concerns.

To address the limitations of the optical-layering approach and expedite multi-vendor interoperability, this work proposes a more direct IP standards-based approach for closer and efficient IP-WDM integration. The proposed approach combines recent advances in IP multiprotocol label switching (MPLS) traffic engineering control plane constructs[3,7] with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks, the "lambda-labeling" approach extends the MPLS label-switching concepts to include wavelength-switched lightpaths. Optical nodes are treated as IP MPLS devices, termed hereafter as Optical-Lambda Switch Router (O-LSR) nodes, where each O-LSR node is assigned a unique IP address. Thus, an IP-over-WDM network can have a uniform control plane based on MPLS and its extensions (e.g., MPλS) (Figure 6-2). This allows sharing of information between the WDM layer and the IP layer while enabling IP traffic to directly access the WDM channels. Therefore, an IP-over-WDM architecture can effectively coordinate LSP determination and protection/restoration to deliver optimal performance. Because the proposed approach for the design of control planes for OXCs is based on MPLS traffic-engineering control plane model, the following several sections will present the requirement of the OXC control plane, give an overview of traffic-engineering in IP networks using MPLS, and illustrate how to extend MPLS to MPλS.

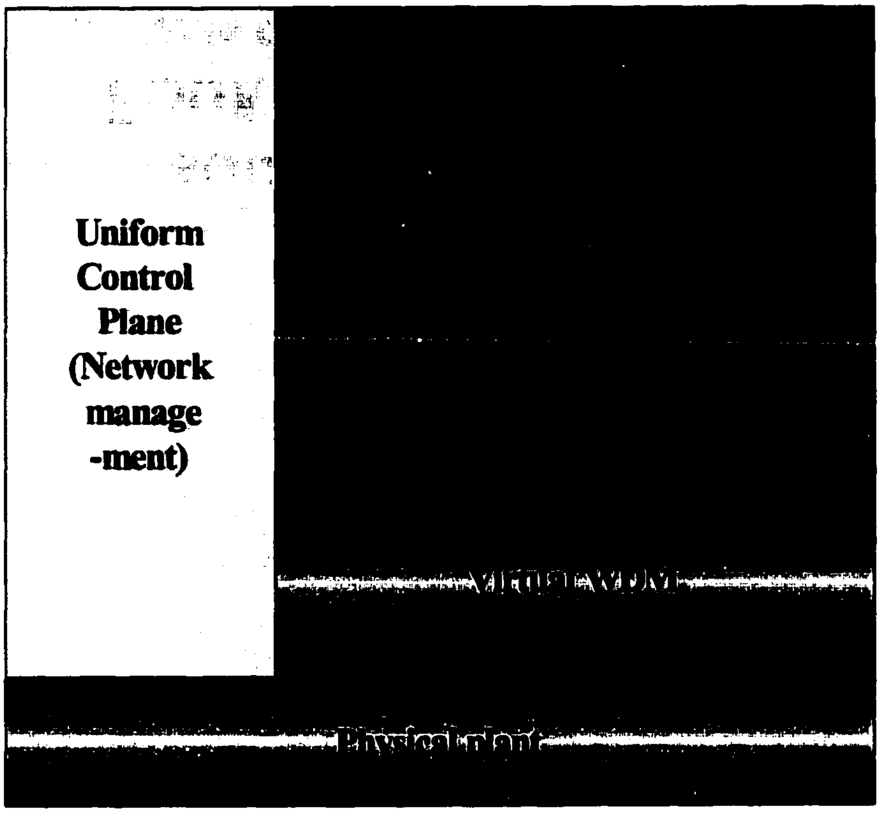


Figure 6-2: An IP-based optical internetworking protocol stack.

Figure 6-3 shows the node structure in hybrid IP-centric DWDM-Based optical networks. The node includes simple electronic dynamic controller, which is used to control optical switch fabric. The switch can be a WSXC or a WIXC, if wavelength conversion is allowed. The optical node uses out of band signaling channel to exchange information with other optical nodes. This information may include the state of individual fibers and the state of each wavelength inside each fiber. Label Switched Routers (LSRs) process traffic in the electrical domain on a packet-by-packet basis. OXCs processing unit is one wavelength. The optical network provides the connectivity between LSRs over switched optical paths.

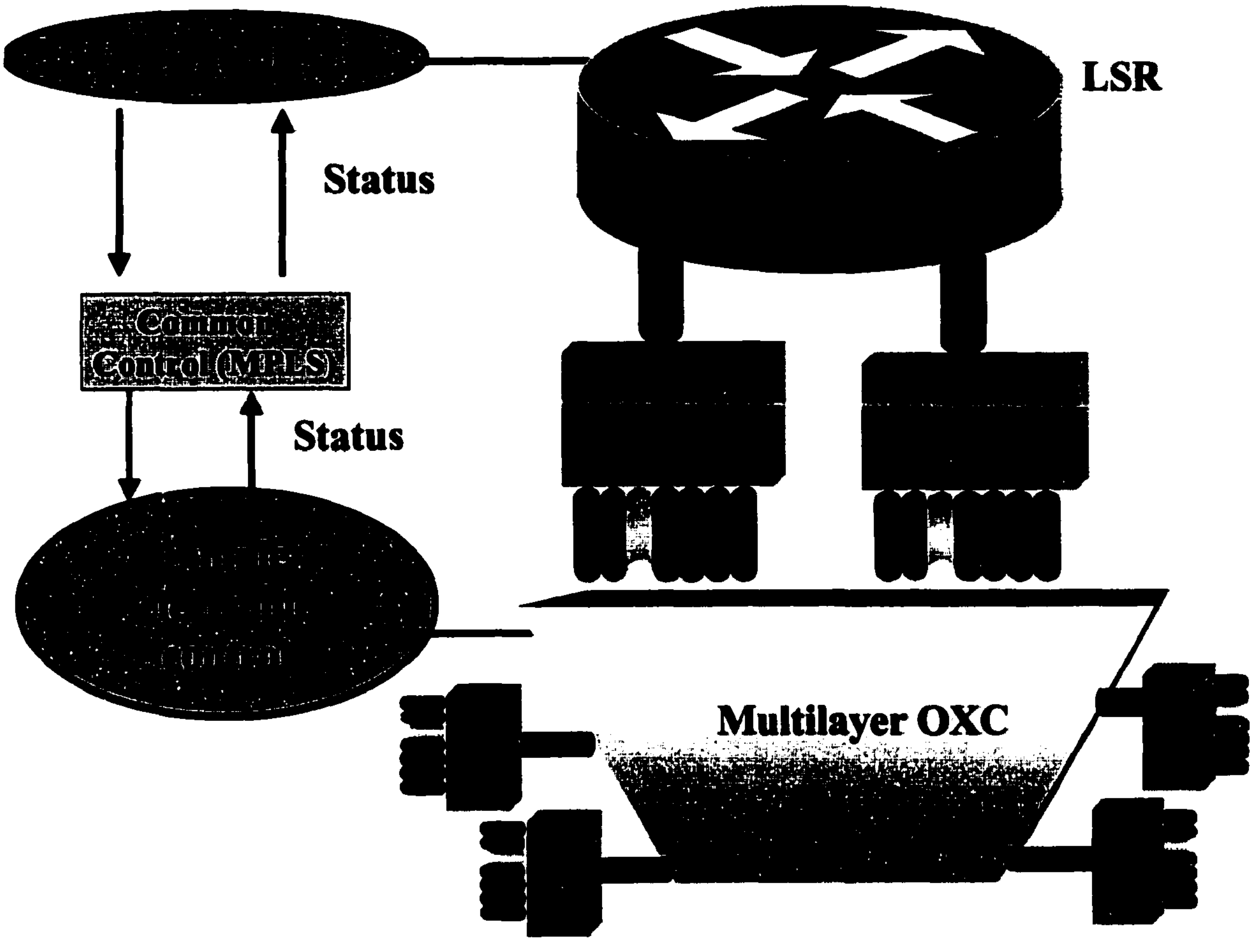


Figure 6-3. A node structure for an MPLS-based optical system.

6-2-2. Overview of MPLS

MPLS introduces a new forwarding paradigm for IP networks. The idea is similar to that in asynchronous transfer mode (ATM) and frame relay networks. A path is first established using a signaling protocol; then a label in the packet header, rather than the IP destination address, is used for making forwarding decisions in the network. In this way, MPLS introduces the notion of connection-oriented forwarding in an IP network. MPLS thus offers a new solution for the third requirement for traffic engineering, establishing a path and sending traffic along that path. This provides the network engineer with a level of functionality equivalent to what virtual circuits provide in ATM networks. In the absence of MPLS, providing even the simplest traffic engineering functions (e.g., explicit routing) in an IP network is very cumbersome.

Two signaling protocols may be used for path setup in MPLS: the Label Distribution Protocol (LDP) and extensions to RSVP. The path set up by the signaling protocol is called a label switched path (LSP). Routers that support MPLS are called label switched routers (LSRs). An LSP typically originates at an edge LSR, traverses one or more core LSRs and then terminates at another edge LSR. The ingress edge LSR maps the incoming traffic onto LSPs using the notion of a forwarding equivalence class (FEC). An FEC is described by a set of attributes such as the destination IP address prefix, type of service (TOS) fields, or IP protocol. All packets that match a given FEC will be sent on the LSP corresponding to that FEC. This is done by pre-appending the appropriate label to the IP packet. The core LSRs forward labeled packets using only information contained in the label; the rest of the IP header is not consulted. When an LSR receives a packet it looks up the entry in its label information base (LIB), and determines the output interface and new outgoing label for the packet. Finally, the egress edge LSR will remove the label from the packet and forward it as a regular IP packet.

While MPLS provides a method to set up explicit paths and forward traffic on them, it does not address the issue of how to find paths with constraints. Routing protocols as currently defined typically only advertise reachability information along with an administrative cost for the links. To enable the computation of routes with constraints, the IETF is working on extending the commonly used IGPs-OSPF and IS-IS - to carry additional information about links. The information includes maximum link bandwidth, maximum reservable bandwidth, current bandwidth reservation at each of eight priority levels, a default traffic engineering metric, and the resource class or color of the link.

Once we have all of this information about every link in the network, we need a path selection algorithm. The source router is basically responsible for computing the complete path all the way to the destination, and then initiating path setup using the signaling protocol. Thus, all routers in the network do not need to agree on the path selection algorithm, and it is left to implementers to decide what path selection algorithm to use. Typically, the constraint-based path selection procedure will involve pruning the database to remove links that are ineligible, due to either insufficient bandwidth or the policy constraints imposed. A shortest path algorithm is then run on the pruned topology to find a route that satisfies the required criteria.

In an MPLS network an LSP must be set up and labels assigned at each hop before traffic forwarding can take place. There are two kinds of LSPs based on the method used for determining the route: control-driven LSPs (also called hop-by-hop LSPs), and explicit routed LSPs (also referred to as constrained-based routed LSPs, CR-LSPs). When setting up a CR-LSP, the rout for the LSPs is specified in the set up message.

6-2-3. Generic Requirements for the OXC Control Plane

In this paragraph, we give a brief description of the characteristic of multi-layer OXC. Multi-layer OXC structure contains wavelength selective cross-connect (WSXC) or wavelength interchange cross-connect (WIXC) and fiber cross-connect (FXC). A WSXC/WIXC is a path switching element in an optical transport network that establishes routed paths for optical channels by locally connecting an optical channel from an input port (fiber) to an output port (fiber) on the switch element. The Demultiplexers demultiplex each fiber into constituent wavelengths. Space switches (wavelength routers) between Demultiplexers and Multiplexers perform space switching for each wavelength, and Multiplexers multiplex wavelengths onto different fibers. For example, Figure 6-4 shows 4×4 eight wavelengths WDM wavelength selective cross-connect (WSXC). For wavelength interchange cross-connect (WIXC), there are wavelength converters between space switches and multiplexers, thus, a path can have different wavelengths on subsequent links. FXC performs fiber switching, the switch unit is a whole fiber.

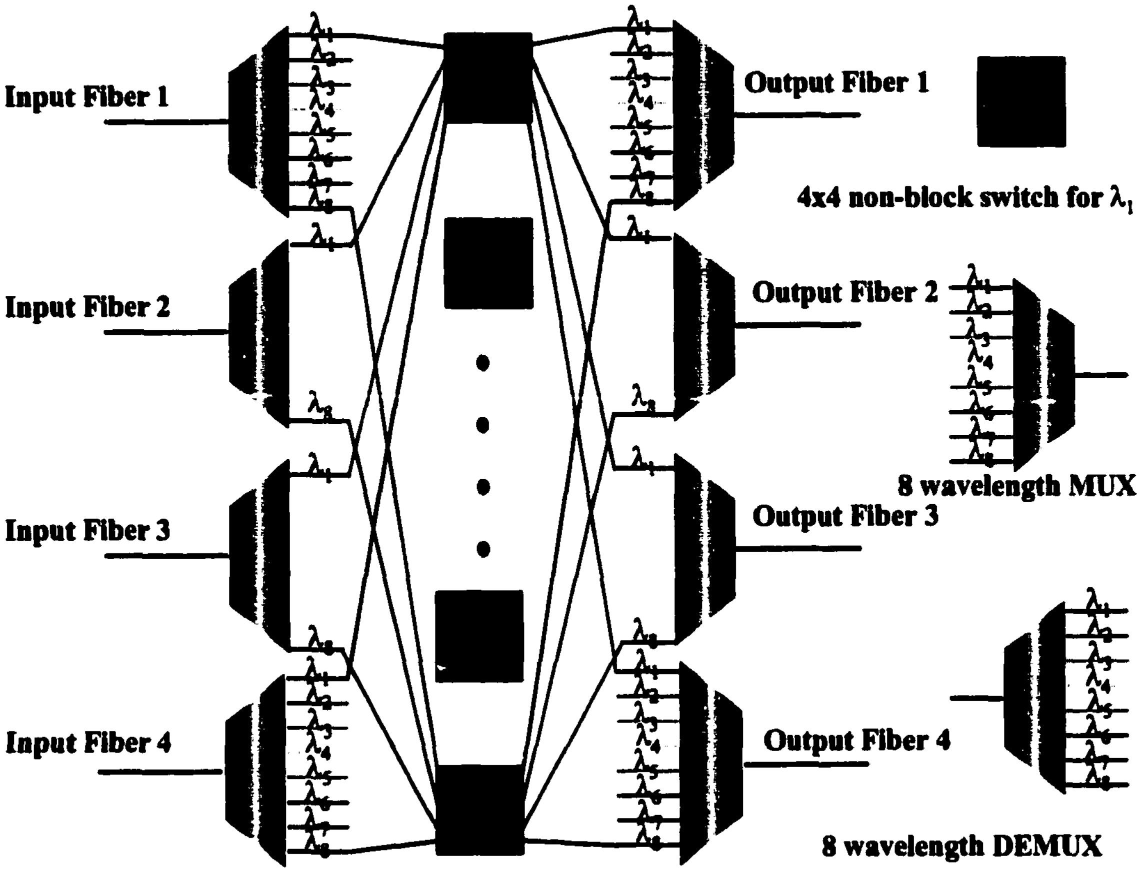


Figure 6-4: Wavelength Selective Cross-connect

The following section contains the requirements for the OXC control plane, with emphasis on the routing components of these requirements. There are three key aspects to these requirements:

(1) The capability to establish optical channel trails expeditiously, (in seconds or even milliseconds rather than days or months).

(2) The capability to support traffic engineering functions, (see note below)

(3) The capability to support various protection and restoration schemes.

Note: the introduction of DWDM and automatically switched optical networks is unlikely to eliminate the need for traffic engineering. Instead, it will simply mandate OXCs to also support some traffic engineering capabilities.

Historically, the "control plane" of optical transport networks has been implemented via network management. This approach has the following detrimental effects:

(1) It leads to relatively slow convergence following failure events (typical restoration times are measured in minutes, or even days and weeks especially in systems that require explicit manual intervention). The only way to expedite service recovery in such environments is to pre-provision dedicated protection channels.

(2) It complicates the task of interworking equipment from different manufacturers, especially at the management level (generally, a custom "umbrella NMS or OSS" is required to integrate otherwise incompatible Element Management Systems from different vendors).

(3) It precludes the use of distributed dynamic routing control in such environments.

(4) It complicates the task of inter-network provisioning (due to the lack of EDI between operator NMSs).

6-2-4. Overview of the MPLS Traffic Engineering Control Plane

Let us now discuss the components of the MPLS traffic engineering control plane model. The MPLS traffic engineering control plane is a synthesis of new concepts in IP traffic engineering (enabled by MPLS) and the conventional IP network layer control plane. The high level requirements for traffic engineering over MPLS were articulated in RFC-2702.[8] It is the combination of the notions defined in RFC- 2702 (including relevant extensions) with the conventional IP control plane constructs that effectively establishes a framework for the MPLS traffic engineering control plane model. [9]

The components of the MPLS traffic engineering control plane model include the following modules:

- Automatic topology discovery. This means an OXC can dynamically learn the network topology without manual intervention, resulting in fast topology convergence.

- State information dissemination, which is used to distribute relevant information concerning the state of the network, including topology and resource availability information.

  In the MPLS context, this is accomplished by extending conventional IP link state interior gateway protocols to carry additional information in their link state advertisements. [14, 15]

- Path selection, which is used to select an appropriate route through the MPLS network for explicit routing. It is implemented by introducing the concept of constraint-based routing which is used to compute paths that satisfy certain specifications subject to certain constraints, including constraints imposed by the operational environment. [8]

- Path management, this concerns the establishment, maintenance, and tearing down of the LSPs through a signaling protocol, such as Constraint-based Routed Label Distributed Protocol (CR-LDP) or Resource Reservation Protocol (RSVP). CR-LDP appears more favorable because of its unique properties, e.g., hard state, reliable transport mechanism, pinning.[9]

These components of the MPLS traffic engineering control plane are separable, and independent of each other. This is a very attractive feature because it allows an MPLS control plane to be implemented using a composition or synthesis of best of breed modules. In RFC-2702,[17] several new MPLS control plane capabilities were proposed that allow various traffic engineering policies to be actualized in MPLS networks. Many of these capabilities are also relevant and applicable to automatically switched optical transport networks with reconfigurable OXCs.

We summarize some of these capabilities below, focusing on the set of attributes that can be associated with traffic-trunks. A traffic-trunk is an aggregation of traffic belonging to the same class which is forwarded through a common path. In general, the traffic-trunk concept is a technology independent abstraction. In Ref.,[17] it was used within the context of MPLS and allowed certain attributes of the traffic transported through LSPs to be parameterized. The traffic-trunk concept can also be extended, in an obvious manner, to the optical transport network.

The attributes that can be associated with traffic-trunks include:

(1) traffic parameters which indicate the bandwidth requirements of the traffic-trunk.

(2) adaptivity attributes which specify the sensitivity of the traffic-trunk to changes in the state of the network and in particular indicates whether the traffic-trunk can be re-routed when "better" paths become available.

(3) priority attributes which impose a partial order on the set of traffic-trunks and allow path selection and path placement operations to be prioritized.

(4) preemption attributes which indicate whether a traffic-trunk can preempt an existing traffic-trunk from its path.

(5) resilience attributes which stipulate the survivability requirements of the traffic-trunk and in particular the response of the system to faults that impact the path of the traffic-trunk.

(6) resource class affinity attributes which further restrict route selection to specific subsets of resources and in particular allow generalized inclusion and exclusion policies to be implemented.

Other policy attributes and options are also defined by Awduche et al in RFC-2702[17] for traffic-trunks, including policing attributes (policing is irrelevant in the OXC context). Concepts of subscription (booking) factors are also supported to either bound the utilization of network resources through under-subscription or to exploit statistical multiplexing gain through over-subscription (this aspect is also not very relevant in the OXC context).

It should be clear that a subset of these capabilities can be mapped onto an optical transport network by substituting the term "traffic-trunk" with the term "optical channel trail". The MPLS control plane also supports the notion of abstract nodes. An abstract node is essentially a set of nodes (e.g., a subnet, an autonomous system, etc) whose internal topology is opaque to the origination node of an explicit LSP. So, in the most general manner, the route of an explicit LSP (or traffic-trunk) can be specified as a sequence of single hops and/or as a sequence of abstract nodes.

The MPLS control plane is very general and is also oblivious of the specifics of the data plane technology. In this regard, the MPLS control plane can be used in conjunction with a data plane that (a) does not necessarily process IP packet headers and (b) does not know about IP packet boundaries. For an existence proof, note that the MPLS control plane has been implemented on IP-LSRs, ATM-LSRs, and Frame Relay-LSRs. The MPLS control plane may also be implemented on OXCs.

6-2-5. Synthesizing the MPLS Traffic Engineering Control Plane with OXCs

Given that that both OXCs and LSRs require control planes, one option would be to have two separate and independent control planes - one for OXCs, and another for LSRs. To understand the drawbacks of this approach, especially in IP-centric optical internetworking systems, one need to look no further than the experience with IP over ATM, where IP has its own control plane (BGP, IS-IS, OSPF), and ATM its own control plane (PNNI).[17-18]

Given that the control planes for both OXCs and LSRs have relatively similar requirements, an alternative approach is to develop a uniform control plane that can be used for both LSRs and OXCs. Such a uniform control plane will eliminate the administrative complexity of managing hybrid optical internetworking systems with separate, dissimilar control and operational semantics. Specializations may be introduced in the control plane, as necessary, to account for inherent peculiarities of the underlying technologies and networking contexts.

All of the above observations suggest, therefore, that the MPLS Traffic Engineering control plane (with some minor extensions) would be very suitable as the control plane for OXCs. An OXC that uses the MPLS traffic engineering control plane would effectively become an IP addressable device. The establishment of optical channel trails, optical transport network (OTN) traffic engineering functions,[12] and protection and restoration capabilities would be provided by the MPLS Traffic Engineering.

An out-of-band IP communications system can be used to carry and distribute control traffic between the control planes of OXCs, perhaps through dedicated supervisory channels (using e.g., dedicated wavelengths or channels, or an independent out-of-band IP network). In this environment, SNMP, or some other network management technology, could be used for element management. From the perspective of control semantics, an OXC with an MPLS Traffic Engineering control plane would resemble a Label Switching Router. If the OXC is a wavelength routing switch, then the physical fiber between a pair of OXCs would represent a single link in the OTN network topology. Individual wavelengths or channels would be analogous to labels. IS-IS or OSPF, with extensions for traffic engineering[15-16] would be used to distribute information about the optical transport network topology and information about available bandwidth and available channels per fiber, as well as other OTN network topology state information. This information will then be used to compute explicit routes for optical channel trails.

An MPLS signaling protocol, such as RSVP extensions or CR-LDP,[10-11] will be used to instantiate the optical channel trails. Using MPLS signaling protocol, for example, the wavelength information or optical channel information (as the case may be) will be carried in the LABEL object, which will be used to control and reconfigure the OXCs. The use of a single control plane for both LSRs and OXCs introduces a number of interesting (and potentially advantageous) possibilities. A single control plane (MPLS Traffic Engineering) would be able to span both routers and OXCs. In such an environment a Label Switching Path could traverse an intermix of routers and OXCs, or could span just routers, or just OXCs. This offers the potential for real bandwidth-on-demand networking, in which an IP router may dynamically request bandwidth services from the optical transport network.

To bootstrap the system, OXCs must be able to exchange control information. One way to support this is to pre-configure a dedicated control wavelength between each pair of adjacent OXCs, or between an OXC and a router, and to use this wavelength as a supervisory channel for exchange of control traffic. Another possibility, which has already been mentioned, is to construct a dedicated out of band IP network for the distribution of control traffic. Even though an OXC equipped with an MPLS traffic engineering control plane would (from a control perspective) resemble a Label Switching Router, there are some important distinctions and limitations. One distinction concerns the fact that there are no analogs of label merging in the optical domain. This implies that an OXC cannot merge several wavelengths into one wavelength. Another distinction is that an OXC cannot perform the equivalent of label push and pop operations in the optical domain. This is because the analog of a label in the OXC is a wavelength or an optical channel, and the concept of pushing and popping wavelengths is infeasible with contemporary commercial optical technologies. In the proposed control plane approach, an OXC will maintain a WFIB (Wavelength Forwarding Information Base) per interface (or per fiber). This is because lambdas and/or channels (labels) are specific to a particular interface (fiber), and the same lambda and/or channel (label) could be used concurrently on multiple interfaces (fibers).

The MPLS traffic engineering control plane is already being implemented on data plane technologies that exhibit some of the aforementioned distinctions. For example, an ATM-LSR supports only a subset of the MPLS functionality. In particular, most ATM-LSRs are incapable of merging Label Switching Paths, and may not be able to perform label push/pop operations as well. Also, similar to the approach proposed here for OXCs, ATM-LSRs have per interface LFIB (Label Forwarding Information Base).

Yet another important distinction concerns the granularity of resource allocation. An MPLS Label Switching Router (LSR), which operates in the electrical domain. can potentially support an arbitrary number of LSPs with arbitrary bandwidth reservation granularities (bounded by the maximum reservable bandwidth per interface and the amount of required control overhead). In sharp contrast, an OXC can only support a relatively small number of optical channel trails (this may change as the technology evolves), each of which will have coarse discrete bandwidth granularities (e.g., OC-12, OC-48, and OC-192). A special degenerate case occurs when the control plane is used to establish optical channel trails which all have a fixed bandwidth (e.g., OC-48).

If the bandwidth associated with an LSP is small relative to the capacity of an optical channel trail, then very inefficient utilization of network resources could result if only one LSP is mapped onto a given optical channel trail. To improve utilization of resources, therefore, it is necessary to be able to map several low bandwidth LSPs onto a relatively high capacity optical channel trail. For this purpose, a generalized notion of "nested LSPs" may be used. Note that since an OXC cannot perform label push/pop operations, the start/end of a nested LSP has to be on a router (as nesting requires label push/pop). Also note that in this nesting situation, it is the wavelength of the "container" optical channel trail itself that effectively constitutes the outermost label.

The transparency and multiprotocol properties of the MPLS Control Plane approach would allow an OXC to route optical channel trails carrying various types of digital payloads (including IP, ATM, SONET, etc) in a coherent and uniform way. Figure 6-5 shows the extension of MPLS in optical networks. In optical network, lambda can be considered as switching labels. CR-LDP provides real time channel provisioning, XC1 (Ingress OXC) generates the Constraint-based routing (based on physical topology database) to get explicit route for optical channel between LSR1 and LSR2, i.e., XC1→XC4→XC7→XC8, here XC8 is egress OXC. XC1 sends Lambda request message to XC4, XC4 sends Lambda mapping information through ACK message, using the same way, the path setting is set up through lambda request and mapping process.

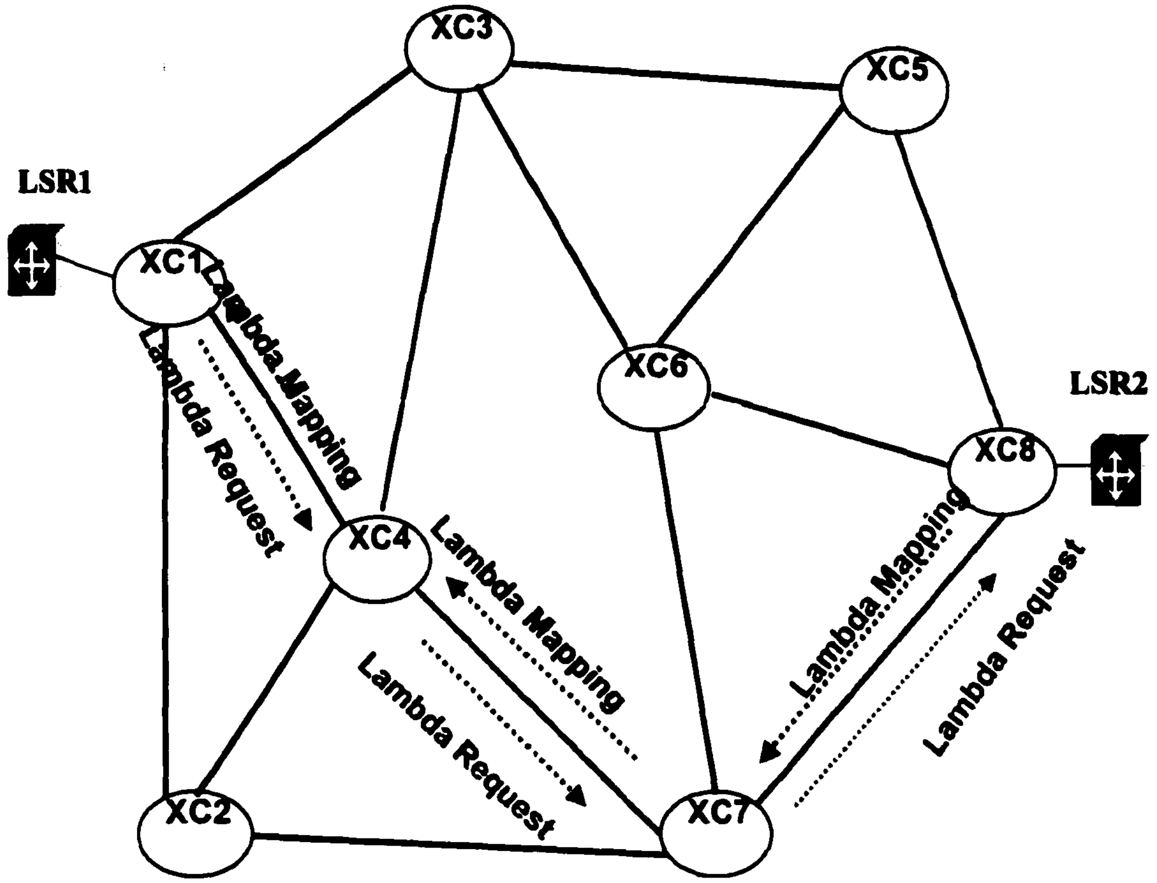


Figure 6-5 illustrates the extension of MPLS in optical networks

6-3. Joint Protection/Restoration at the IP/WDM Layers

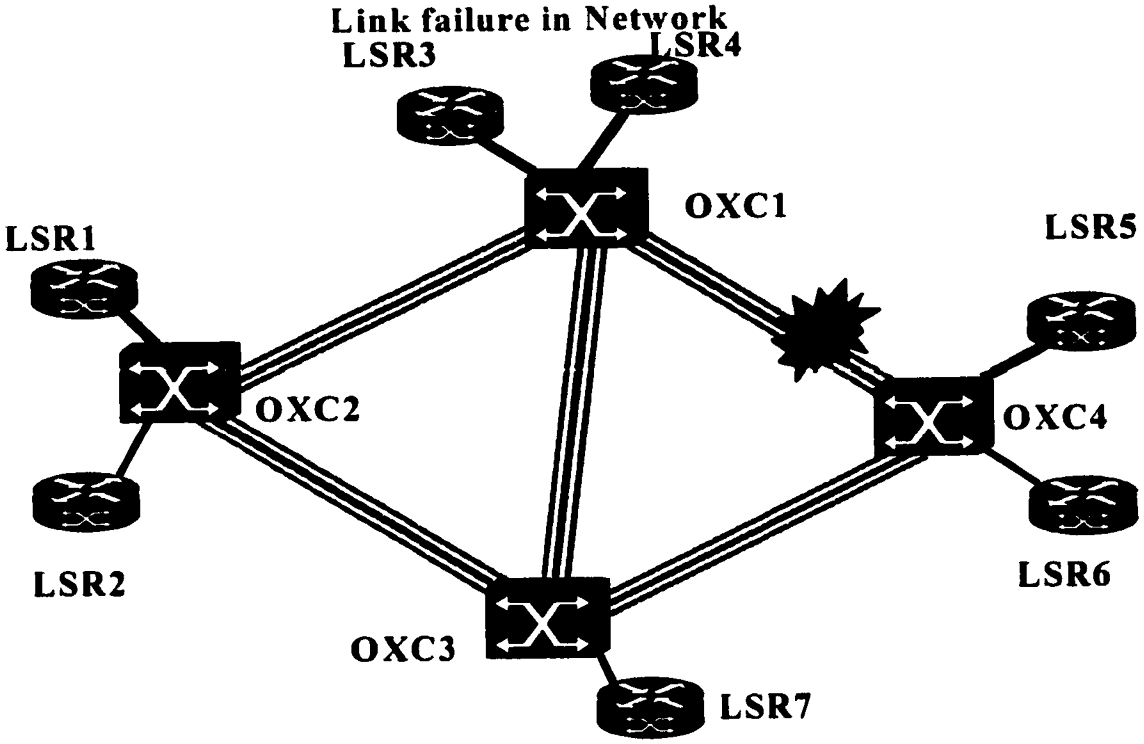
Since each channel operates in a Gb/s range in IP/WDM networks, even a single failure event can be catastrophic. IP layer protection scheme uses traffic rerouting when failure occurs inside the working entity. Although MPLS promises IP layer protection with fast restoration and path switching, fast recovery is still hampered by LSP failure detection.[8] It should be noted that even a single fiber cut or node failure will affect multiple LSPs, which means that hundreds of ingress routers of LSPs should be notified requiring intensive computation if MPLS signaling is used. Multiple LSP failures also lead to even more LSRs to update the topological and forwarding information causing the network to become potentially more unstable. Hence the optical protection/restoration cannot be avoided in an IP-over-WDM network. In order to achieve maximum network availability and reliability, the implementation of protection/restoration function must be coordinated at both IP and WDM layers.

The introduction of MPLS and its extension gives the opportunity for network operator to provide service-orientated protection/restoration. Joint protection/restoration requires both LSRs and OXCs to support failure detection, failure notification, and protection mechanisms, and for CR-LDP or RSVP signaling to support configuration of working and protection paths. Each LSR maintains the forward equivalence class (FEC) – the next-hop label forwarding entry (NHLFE) – mapping for the incoming packets. This mapping can be changed for rerouting traffic from a failed path to an alternative path or load balancing over multiple paths. The label stack and merging are allowed in IP/MPLS, i.e., each LSP may contain several small bandwidth LSPs. As to OXC, it executes circuit switching and maintains a wavelength-forwarding table. OXC performs lambda switching according to the entries in the forwarding table, which contains the information on how to handle an incoming connection, such as the outgoing fiber port, outgoing wavelength if wavelength conversion capability exists. The fiber or channel level protection/restoration can be implemented by modifying the entries in the wavelength-forwarding table. CR-LDP or RSVP implements the information exchange between OXCs or LSRs. The in-band or out-of-band signaling channel is used for conveying these messages.

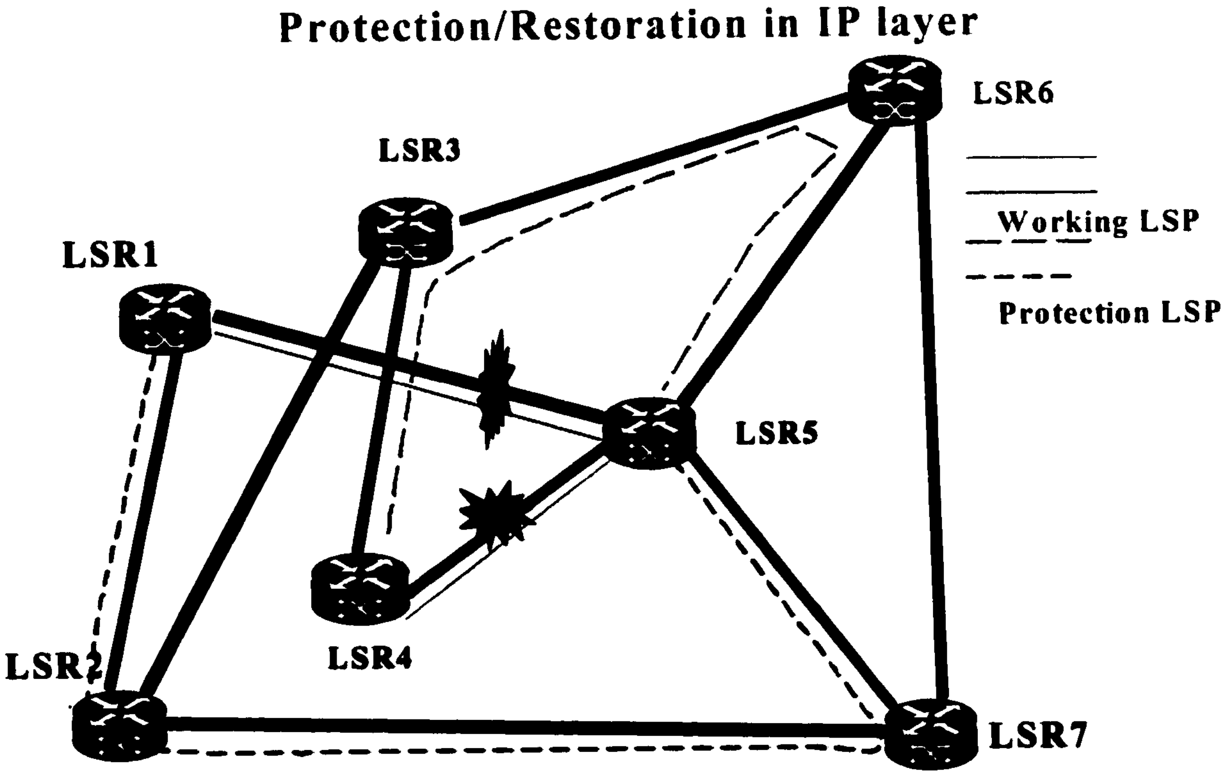
Selection of the working LSP and updating a protection path is very critical. In WDM, the working capacity and backup capacity assignment problem has been well known as an RWA problem. It has been shown to be NP-complete.[3] Many researchers have proposed optimization schemes to formulate the RWA problem with ILP or the modified ILP algorithms similar to the HPS in this paper. The RWA with real time requests becomes a dynamic lightpath establishment (DLE) problem. To address this problem, dynamic heuristic algorithms with the various cost metrics have been proposed, e.g., Least Congested Path (LCP) algorithm, Dijkstra's shortest path algorithm.[13,16] However, using heuristic methods may lead to higher blocking probability. If network operators can run the optimization schemes (offline) over longer intervals to continually tune the network performance, the network will allow more lightpath setups.[15] Recent developments in MPLS offer a possible solution to IP/WDM routing problem concerning traffic engineering at both layers.[11,15] As indicated in[11], essential to the use of MPLS with OXCs is the ability to aggregate LSPs by using the notion of "nested" LSP. The nested LSP means that the MPLS control plane could use an LSP as a link to form another LSP, and that other LSP, in turn, could be used as a link to form some other LSP, etc. For example, in IP centric optical networks, the MPLS control plane uses optical LSP as a link to form IP-LSP.

The failure detection is one of the crucial functions for failure recovery. Fault detection at the IP layer is hampered by the fact that detecting an LSP failure at the ingress LSR can take a long time, since ingress LSR is responsible for setting up, tearing down and maintaining LSP via explicit routing. After a break in an LSP hop, notification messages are propagated along the LSP intermediate nodes back to the ingress LSR. Message processing occurs at each hop and this adds delay in informing the ingress LSR that the LSP has failed. In WDM layer, failure detection is fast due to physical methods (e.g., loss of light, loss of carrier signal). Optical monitoring schemes have been proposed for transparent optical channels,[12-13] but they still will take some time to be standardized. The endpoints of the affected optical channels detect the failure more quickly because the signaling of the failure is very fast (e.g., using messages in optical packets similar to AIS signals in SONET) and the number of optical channels in the failed link is much less than the number of the affected LSPs. So, in WDM networks, the detection of a failed connection is fast and scales well for all the connections on the failed link.

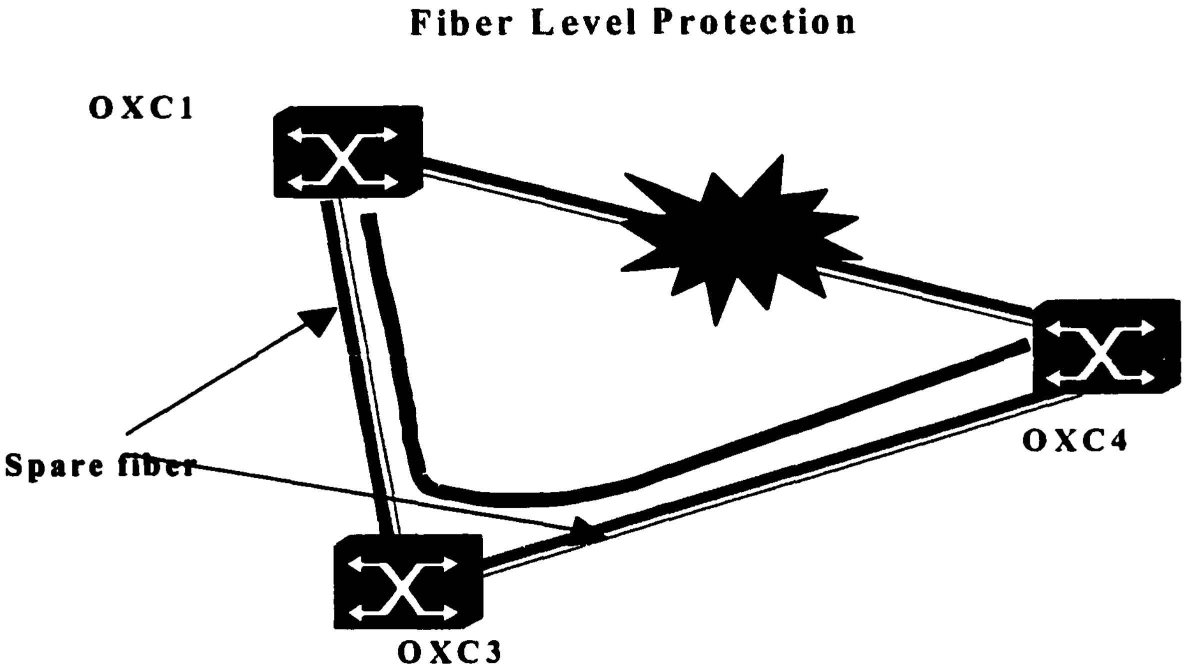
To deal with this problem, IP/WDM provides three options according to protection granularity: fiber protection (at the OMS level), channel protection (at the OCh level), and higher layer protection (at the IP layer). Here we take a simple network (Figure 6-6) as an example to show how these three protection options inter-work.


Link failure in Network
LSR3
LSR4
OXC1
LSR1
LSR5
OXC2
OXC4
LSR2
LSR6
OXC3
LSR7

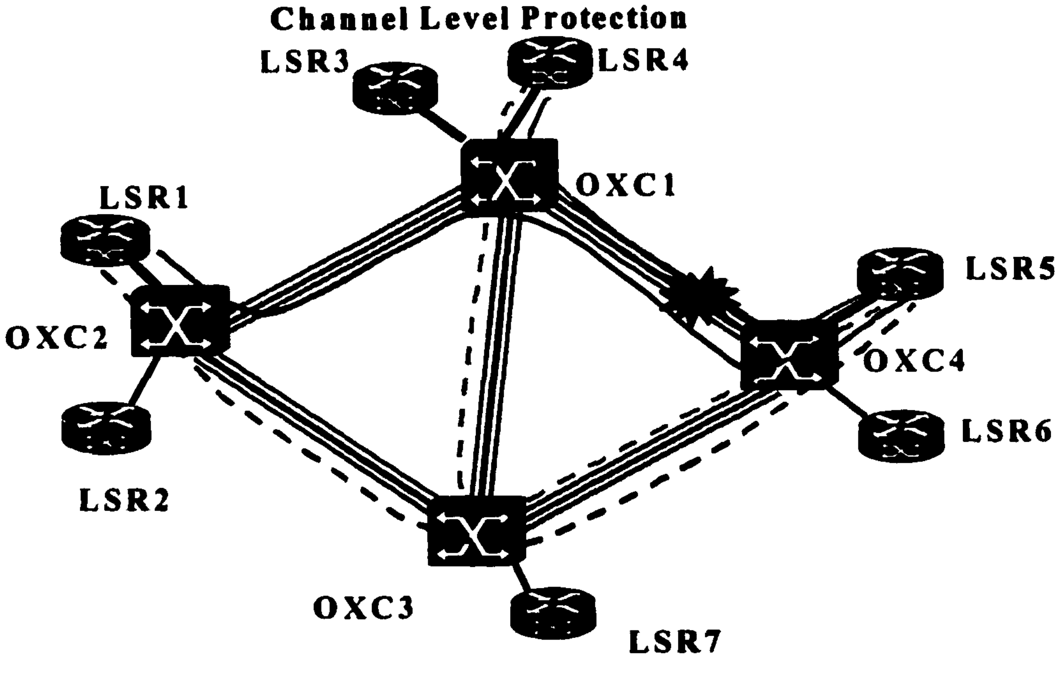
(a)


Protection/Restoration in IP layer
LSR6
LSR3
Working LSP
LSR1
Protection LSP
LSR5
LSR4
LSR2
LSR7

(b)



(c)



(d)

Figure 6-6: An example demonstrates joint protection scheme in IP/WDM a) The cable cut shows in physical topology; b) Protection is implemented in virtual topology (router-router connectivities); c) Fiber level protection needs the spare fibers to reroute all the traffic carried by the failed cable; d) Channel level protection reroutes the traffic carried by the failed lightpaths among the working fibers.

The network consists of four OXCs and seven LSRs. The physical connections are shown in Figure 6-6 (a). The virtual topology shows the router-to-router connections (Figure 6-6 (b)) where one router-to-router link may span several physical links. Routing and wavelength assignment algorithm doesn't consider wavelength conversion since it is quite expensive and technology is not yet mature. Also, the constraint that the wavelength is continuous (end-to-end) has to be considered. Assume there is a fiber cut between OXC1 and OXC4, and the two lightpaths, which connect LSR4 with LSR5 and LSR1 with LSR5, respectively, are affected. For fiber protection, once OXC1 detects the failure, it will trigger protection mechanism, and the predetermined protection is used. OXC1 consults the database, and knows that the fiber protection for the failed working fiber will be OXC1 →OXC3→OXC4 (Figure 6-6 (c)). OXC1, therefore, sends notification messages to OXC1, OXC3, OXC4, and modifies the fiber interface element in the entry of the wavelength-forwarding table while keeping the wavelength element untouched. Through fiber switching, the fiber protection route is set up. In OXC1, the traffic is switched to the protection fiber, and, in OXC4, the traffic is switched back to the normal status.

At the OCh level protection scheme, the traffic carried by two lightpaths has to be recovered. The protection paths are reserved at the same time as the working lightpaths, and the protection path selection process is the same as the working path selection process, except that it adds additional constraints (e.g., the working lightpath cannot share the same failed link as the protection lightpath) to the routing protocol which runs over the link state database. The protection lightpath can use a different wavelength than the working lightpath wavelength provided wavelength agility is allowed. After OXC1 detects failure, it sends failure notification messages, encapsulated in TLVs (LDP message format), to the protection switched OXCs, which are responsible for switching traffic from working lightpaths to protection lightpaths. In our example, OXC2 is protection switched OXC. A lightpath from LSR1 to LSR5 expressly bypasses (i.e., cut-throughs) OXC1 and OXC4 without getting into the attached routers. Once OXC2 gets alarms, it will activate the protection path OXC2→OXC3→OXC4 by signaling. A lightpath from LSR4 to LSR5 will be protected by an alternate path OXC1→OXC3→OXC4 (Figure 6-6 (d)).

The above two optical protection schemes do not impact the virtual topology, since the lightpaths provide the link for IP connection, and router-to-router links are not changed. In IP layer protection, a router-to-router direct connection between the two ends of a lightpath will get disrupted, which will change the virtual topology. The IP layer protection employs the existing working lightpaths to reroute traffic. The LSRs process the incoming traffic on a packet by packet basis (where the traffic can also be buffered). The edge LSR knows the virtual topology along with the resources utilized, and selects a protection path by running explicit constraint-based routing. For LSR-LSR links, physical link diversity is a major consideration. Due to the multiplexing of the wavelengths it can be difficult to ensure that a physical link failure does not affect two or more lightpaths. When an edge LSR looks for a protection path, it removes the unqualified links (e.g. lightpaths), and then applies the shortest path algorithm to find an alternative path. Since the protection uses the existing lightpaths it may not provide 100% survivability. In order to provide maximum survivability, the intermediate LSRs may drop some low priority traffic (e.g., small bandwidth LSPs), which can be distinguished from the label of a packet. And, for the disrupted traffic, the protection first considers the high priority traffic. The traffic has to undergo O-E-O conversion at intermediate LSRs. In Figure 6-6 (b), traffic between LSR1-LSR5 can be protected by the alternative LSP, which passes LSR1→LSR2→LSR7→LSR5. The traffic between LSR4 and LSR5 can be restored by LSR4→LSR3→LSR6→LSR5. In IP/MPLS, traffic engineering allows for multipath routing, label stacking, and label splitting. Also, the protection granularity is flexible. For example, if a large-granularity LSP cannot be protected, it can be demultiplexed into many small-granularity LSPs. Then each small granularity LSP can have its own protection path, and each working LSP may have multiple protection paths where one of them carries a part of the protected traffic of the working LSP.

6-4. Summary

This chapter has presented an overview of the envisioned IP-centric DWDM-based optical data network architecture. We have also presented and discussed the guidelines of implementing a more direct IP standards-based approach for closer and efficient IP-WDM integration. This is made possible by combining recent advances in IP-MPLS-based traffic-engineering control plane constructs with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks. Finally, we have articulated a view on how to provide a joint protection/restoration scheme that is coordinated at both the IP and WDM layers. There still remains a lot of issues that need to be addressed, e.g., routing stability, coordination between IP and WDM layer protections.

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CHAPTER 7

CONCLUSION

This thesis has addressed the important problem of how to bridge the gap between Dense-Wavelength Division Multiplexed (DWDM) optical networks and the Next-Generation Internet and has examined, at both the physical layer and the higher layers protocol, how the capabilities of DWDM technology can be used: 1) To support the explosive traffic demands of the Next Generation Internet, and 2) To take DWDM from a mere fiber multiplication method to its new phase of becoming the world's intelligent bandwidth infrastructure, that is to evolve DWDM technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer.

Aggregate bandwidth required by the Internet in the US by the year 2005 is expected to be in excess of 35 Terabytes/sec. To meet this anticipated demand, this work has presented a novel, dynamic, survivable, and scalable ultra-high speed DWDM-based Self-Healing Ring (SHR) network topology capable of supporting up to 100 channels (wavelengths) at 2.5-10 Gb/s per channel for an aggregate network capacity in the order of a Tb/s per fiber. Specifically, this thesis has examined, through computer simulation and modeling, the technological requirements and has assessed the performance analysis and feasibility for implementing a dynamic and scalable ultra-high speed transport network fabric based on SHR network topology and DWDM technology. To ensure that the network is scalable, a network planning and optimization strategy, at the initial phase of the system design, that allows a smooth network evolution while maintaining adequate end-to-end performance, independent of the network size, for all wavelength signals across the network also has been developed.

The second main issue that this work has addressed is how to move DWDM from a mere "dumb" fiber multiplier technology toward an optical networking infrastructure with transport, multiplexing, routing, supervision, and survivability supported at the optical layer. We have investigated two different options for the implementation of one of the most critical networking functionality associated with ultra high capacity transport networks, namely "Network Survivability". The first option has assumed that full protection/restoration functionality could be implemented at the optical layer. In view of this option, we have investigated the potential and limitations of providing full protection/restoration functionality at the optical layer, and whether it makes practical sense, given similar mechanisms that are already available at the higher layers (e.g., SONET/SDH, ATM, IP). Specifically, we have presented a novel mesh-based hybrid optical protection scheme that utilizes multifiber physical links along with hierarchical OXC structure, which is a combination of fiber cross-connects (FXCs) and wavelength selective cross-connects (WSXC's).

The second option has assumed that protection/restoration functionality could be allocated between the optical layer and the data layers. A central issue for the successful implementation of this option is the reduction of the cost and complexity associated with today's multi-layer core transport network architecture. This may be achieved through the elimination of unnecessary network layers, to avoid functional overlap and wasteful duplication, among today's conventional four-layers core transport network model. In this view of reduced or "collapsed" network layers, this thesis has examined the notion of supporting "data directly over optics", where existing TDM systems (e.g., SONET/SDH) play a diminishing role, and Optical Transport Networking emerges as the underlying transport infrastructure for the envisioned "DWDM-based IP-centric optical Internet". To address the limitations of the multi-layering approach, this work has presented an overview of a more direct IP standards-based approach for closer and efficient IP-WDM integration. This approach has combined recent advances in IP multiprotocol label switching (MPLS) traffic engineering control plane constructs with Optical Cross-Connects (OXC) technology to provide a framework for optical bandwidth management and for the real-time provisioning of optical channels in automatically switched optical networks. Finally, having established the notion of mapping IP directly onto the WDM layer, we have presented and developed a simple and integrated hybrid protection/restoration scheme that could be coordinated at both the IP and WDM layers.

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