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DWDM Network Protection/Restoration with Ring/Cycle Topologies

By

Hanxi Zhang, M. Eng.

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Ottawa-Carleton Institute for Electrical Engineering
Department of Electrical & Computer Engineering
Faculty of Engineering
University of Ottawa

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Abstract

In this thesis, we first discuss the differences between plain optical switches and wavelength routers, which are the building blocks for static WDM networks and wavelength routing networks respectively. We study the different features of these building blocks, and clarify the different meanings of 'ring/cycle topologies' in those two types of optical WDM networks.

Then we propose a heuristic algorithm to find a set of link-covering rings to be used in WDM network protection/restoration. Our algorithm yields a scalable set of rings that covers most links in a sparse mesh network.

To study whether it is beneficial to use P-cycles instead of pure rings in the WDM ring cover approach, we design a generic linear programming model for comparison purposes. By doing simulation studies with the model, we show that the method of P-cycle cover can only achieve very little performance improvement over pure ring cover. Thus from an engineering point of view, P-cycle cover is not practical.

Finally we propose a distributed protocol to find rerouting paths by P-cycle decomposition, in wavelength routing networks. The restoration performance of the distributed protocol can be very close to the theoretical upper bound under our traffic distribution assumptions. That justifies P-cycle is a highly efficient topology for network protection/restoration.

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Table of Acronyms

		Section of 1st Appearance
ADM	Add Drop Multiplexer	1.1
ATM	Asynchronous Transmission Mode	1.4
BLSR	Bi-directional Link-protection Switching Ring	1.4.1.1
DADM	Digital Add Drop Multiplexer	1.1
DRR	Distributed Ring-based Rerouting	5.1
DWDM	Dense Wavelength Division Multiplexing	1.1
DXC	Digital Cross Connect	1.1
EDFA	Erbium Doped Fiber Amplifier	1.1
ILP	Integer Linear Programming	4.1
IP	Internet Protocol	1.1
LDP	Label Distribution Protocol	1.1
LP	Linear Programming	1.4.2.2
LSA	Link State Advertisement	5.2.1.2
LSP	Label Switched Path	1.1
MPLS	Multi Protocol Label Switching	1.1
MRF	Maximum Rerouting Flow	5.2
OADM	Optical Add Drop Multiplexer	1.1
OEO	Optical/Electronic/Optical	1.1
OSPF	Open Shortest Path First	1.1
OXC	Optical Cross Connect	1.1
P-cycle	Protection Cycle	1.4.2
QOS	Quality Of Service	1.1
RWA	Routing and Wavelength Assignment	1.7
SHR	Self-Healing Ring	1.4.1.1
SLA	Straddling Link Algorithm	1.8
TDM	Time Division Multiplexing	1.1
UPSR	Unidirectional Path-protection Switching Ring	1.4.1.1
WDM	Wavelength Division Multiplexing	1.1

Table of Notations

			Section of 1st Appearance
C_i	=	capacity allocation of cycle i, $i = 1, 2 \ldots K$	4.2
E_{ij}	=	indicator for whether node i is the end node with a smaller ID on link j	5.2.2.2
K	=	total number of candidate rings/cycles	4.2
L	=	total number of links in the network	4.2
M_i	=	number of rerouting paths for the failure of link i, $i = 1, 2 \ldots L$	5.2.2.2
N	=	total number of nodes in the network	3.2
P_i	=	number of protected working wavelengths on link i, $i = 1, 2 \ldots L$	4.2
Q_{ij}	=	indicator for whether link i is on rerouting path j	5.2.2.2
S_i	=	number of spare wavelengths on link i, $i = 1, 2 \ldots L$	5.2.2.2
T_i	=	total wavelength capacity of link i, $i = 1, 2 \ldots L$ $(Ti = W_i + S_i)$ (Each T_i is set arbitrarily to 12)	4.2
U_j	=	minimum number of spare wavelengths along cycle j, $j = 1, 2 \ldots K$	4.2
W_i	=	number of working wavelengths on link i, $i = 1, 2 \ldots L$	4.2
X_{ij}	=	indicator for whether link i is on cycle j	4.2
X'_{ij}	=	indicator for whether link i is straddling cycle j	4.2
$Flow\_X_i$	=	directional flow over link i, which goes from the node with smaller ID to the node with larger ID, $i = 1, 2 \ldots L$	5.2.2.2
$Flow\_Y_i$	=	directional flow over link i, which goes from the node with larger ID to the node with smaller ID, $i = 1, 2 \ldots L$	5.2.2.2
$PATH\_FLOW_{ij}$	=	partial rerouting flow that goes over rerouting path j for the failure of link i, $i = 1, 2 \ldots L, j = 1, 2 \ldots M_i$	5.2.2.2
s	=	one of the two end nodes of the failed link that has a smaller ID	5.2.2.2
d	=	one of the two end nodes of the failed link, which has a larger ID	5.2.2.2

Table of Contents

Chapter 1

Introduction

1.1 Developments in DWDM and DWDM Networking

Dense Wavelength Division Multiplexing (DWDM) [1] is the process of multiplexing signals of different wavelengths onto a single fiber. A DWDM system can be viewed as a parallel set of optical channels, each using a slightly different light wavelength, but all sharing a single transmission medium. This new technique can increase the transmission capacity dramatically without the need for expensive re-cabling, thus cutting down the cost of bandwidth.

The following are some basic components for a DWDM system [2]:

- Flat gain optical amplifiers, such as Erbium-doped fiber amplifiers (EDFA) [1,3].
- Tunable Lasers.
- Fast Tuning receivers.
- Wavelength converters.
- Splitters and combiners, which can be used as building blocks for wavelength multiplexers and demultiplexers.

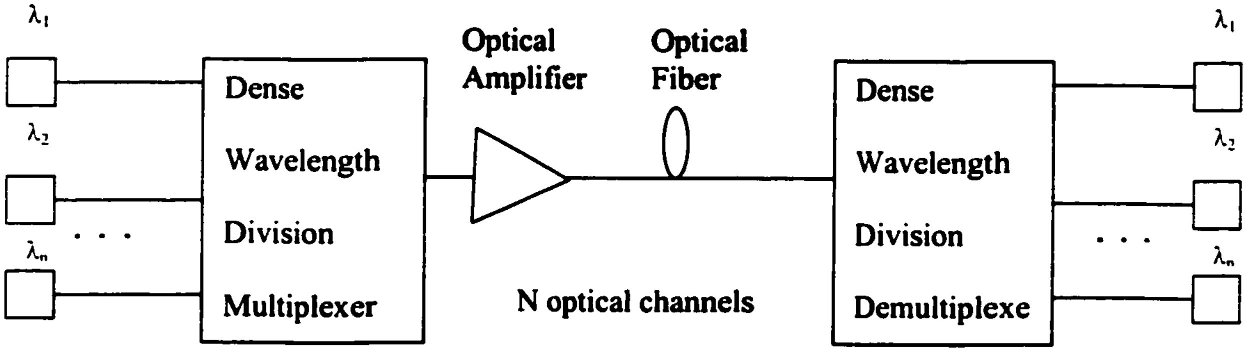


Fig. 1.1 A Point-to-Point DWDM System

Fig. 1.1 depicts the structure of a typical point-to-point DWDM transmission system making use of these components. The optical amplifier is able to amplify multiple wavelengths in a uniform manner, and is generally regarded as the most important enabling component for DWDM transmission.

Nowadays most DWDM systems work in either 1310nm or 1500 nm frequency window, with minimum channel spacing around 1nm or even less. The dominant factor for channel spacing is the receiver's capability in identifying two closely spaced wavelengths.

DWDM has been very successful as a means of long haul point-to-point data transmission [2]. Since one wavelength can carry up to 10 G bps data stream, and 64 or even more wavelengths per fiber has already been successfully demonstrated, bandwidth becomes much cheaper than before. On the other hand, the electronic switching at network layer is becoming the bottleneck of network throughput, as opposed to link capacity. As recent developments in basic components make into reality more advanced optical sub-systems (which are built with basic components) such as optical cross-connect (OXC) and optical add-drop-multiplexer (OADM), the trend is towards optical-switched transport networks that are based on DWDM technology. As a result, DWDM is being shifted from a point-to-point technology to a networking technology. What makes DWDM networking different from point-to-point DWDM transmission is that there is an optical WDM protocol layer responsible for the set up and tear down of end-to-end lightpaths. This layer also provides usable bandwidth to upper layer protocols, such as IP, ATM, SONET.

DWDM networking can be understood further from two aspects: equipment point of view and protocol point of view.

(I) Equipment point of view

OXCs are capable of selectively switching individual wavelengths, while OADMs are able to add/drop individual wavelengths. Although the controls for both OXCs and OADMs are still electronic, all the switching operations are in the optical domain, regardless of the bit-rate and framing format in the electronic domain. Thus network throughput is elevated dramatically over traditional SONET transport networks, where transmission is optical point-to-point, but switching operations at either digital cross-connects (DXC) or digital add-drop-multiplexers (DADM) are in the electronic domain. Furthermore, since in DWDM networks both switching and point-to-point transmission are in the optical domain, no more optical/electronic/optical (OEO) conversions are needed.

There are two categories of switching equipments for optical WDM networks: plain optical switches [38,39] and wavelength routers [4,6]. The difference is that wavelength routers have a routing control module while plain optical switches do not.

(II) Protocol point of view

By introducing an optical WDM layer, it is like adding another dimension to the network protocol stack. The major functionalities of this protocol layer include:

1. End-to-end lightpath set up and tear down.
2. WDM layer channel monitoring and management. Some optical domain parameters need to be measured and properly controlled, such as signal-to-noise ratio, channel spacing, crosstalk, attenuation and dispersion.
3. WDM layer protection and restoration.
4. WDM layer traffic engineering.

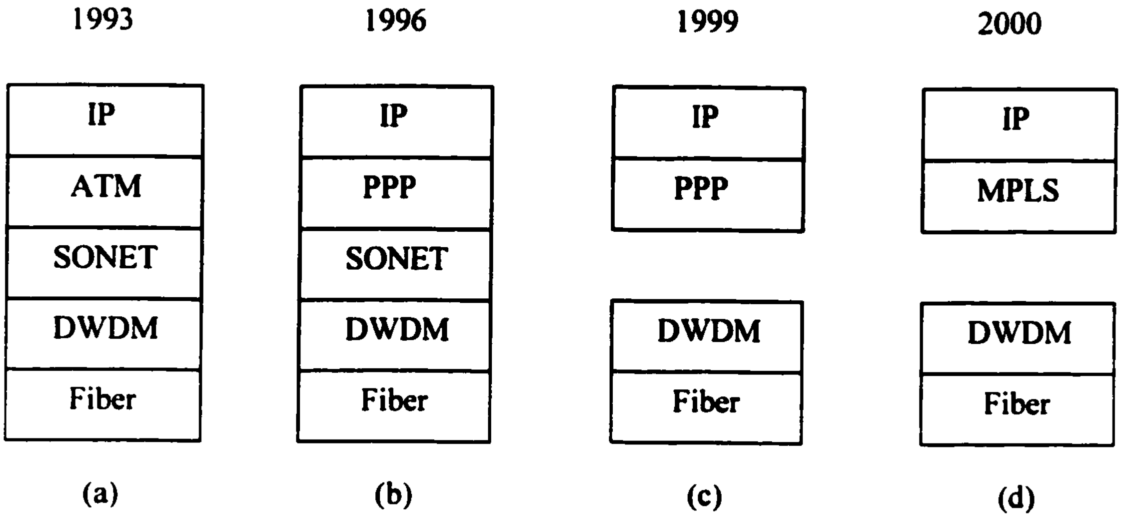


Fig. 1.2 **Evolution of the Protocol Stack of DWDM Networks [4]**

Multiple protocol layers co-exist during the early days of DWDM networking, and the protocol stack from the bottom to the top looks like depicted in Fig. 1.2 (a) and (b).

There are a few problems with the functional overlap in the multi-layer approach [4,5]. First of all, the multi-layer approach means the deployment of many costly ATM and SONET equipments, which may not be all necessary. A multi-layer stack introduces undesired latency, because the presence of the high capacity WDM layer obviates the need for time division based multiplexing and traffic grooming. Upon a network failure, each layer tries to perform restoration, and causes a lot of uncontrollable complications. Therefore, in order to reduce the overhead of multi-layer coordination, the trend of protocol stack evolution is to move those functionalities traditionally implemented within ATM/SDH layers either up to IP layer or down to the DWDM layer [6]. The ultimate goal is to run IP directly over DWDM, as shown in Fig. 1.2 (c) and (d). With IP being the dominant network layer protocol, and DWDM layer being able to provide cheaper bandwidth than never before, IP directly over DWDM is expected to be a winning combination [4-6].

In Fig. 1.2 (c) we have two management layers – IP and DWDM. While in the latest IP/MPLS/DWDM solution (also called 'optical lambda switching') as demonstrated in Fig. 1.2 (d), each wavelength is regarded as a 'label' by IP layer via MPLS [7]. In other words, we still have 2 layers, but their managements are more tightly coupled together.

In optical lambda switching, each optical cross-connect is an IP addressable device that is able to do <input port, λ_{in}> to <output port, λ_{out}> mapping. By using MPLS as a generic 'middleware' in-between IP and DWDM, the lambda-labeling approach attaches MPLS control planes onto optical cross-connect equipments and treats them as MPLS nodes [7]. An end-to-end lightpath is equivalent to a discrete granularity label switched path (LSP) between optical MPLS nodes. Those optical MPLS nodes translate label assignments into corresponding wavelength assignments and set up lightpaths by sending instructions to their optical cross-connect matrixes. Some MPLS-based traffic engineering features such as constraint-based routing and explicit routing can be naturally deployed in the optical lambda switching framework.

There are 2 key protocols needed in the optical lambda switching framework: wavelength distribution protocol and wavelength routing protocol [5,6,8,9,10]. Wavelength distribution protocol is derived from label distribution protocol (LDP) in MPLS and used as a signaling protocol to set up (tear down) end-to-end lightpaths. Wavelength routing protocol is a link state routing protocol derived from OSPF [11] and used to collect network topology, the distribution of working/spare wavelengths and other resources. Both protocols are being studied and prototyped in the industry right now [8-10]. Different companies and standardization bodies may use slightly different terminologies for those two protocols, but the whole idea is the same, namely to enable an intelligent and scalable WDM layer that can be seamlessly merged with IP/MPLS.

In summary, the IP/MPLS/DWDM approach integrates the service and transport layers more closely, yielding simpler management and faster response between DWDM and IP layers, as opposed to the multi-layer approach in Figs. 1.2 (a), (b) and (c).

Although optical lambda switching is accepted as the general framework for DWDM networking, there are still many open questions to be answered [6], such as:

- Where exactly is the boundary between electronic technologies and optical technologies?
- What is the network quality of service (QOS) pattern in an optical lambda switching network?
- How should network protection/restoration be coordinated between IP and DWDM layers?

This thesis is focused on addressing the network protection/restoration issues at DWDM layer.

1.2 WDM Layer Network Protection/Restoration

As the network throughput being boosted dramatically in DWDM networks, network survivability becomes a more critical issue than before. A single wavelength channel of multi-gigabits per second can carry the capacity equivalent of tens of thousands of individual conversations and data connections, and in a fiber conduit there can be several tens of fibers, within each there maybe several tens of DWDM channels running. Without proper protection/restoration, single fiber span cut in a DWDM network will lead to very serious economical and social impacts [12].

Suppose that upon a lambda channel failure, we take no action at the DWDM layer, but leave the protection/restoration up to upper layer protocols, such as SONET, ATM and IP. When a failure occurs, SONET layer will detect the failure first and carry on protection switching, then ATM layer will try to re-establish disrupted VP/VC connections, finally IP layer will timeout and try to retransmit lost IP packets. That is a serious problem because we can hardly guarantee a protocol layer finishes all the restoration operations before another round of restoration starts one layer up. The results of multi-layer restoration are not well understood and uncontrollable [4,5].

Therefore it is important that protection and restoration take place at DWDM layer, to fix up disrupted traffic at the wavelength level. In other words, we would like to protect and restore 'macro' flows at the first place. As we have discussed at the end of Section 1.1, the specifications of optical lambda switching is not quite done yet, and there are a lot of research going on about DWDM layer protection/restoration.

1.3 Network Protection/Restoration Methods

Literally, protection means those proactive measures taken before a failure occurs, and restoration means those reactive measures taken upon a failure. A protection method always has a certain restoration operation associated with it. On the other hand, a restoration method may not have any proactive measures taken in advance. An example is the packet retransmission in IP layer restoration.

Generally speaking, whatever method we use for network protection/restoration, there are always 2 key factors involved: topology and protection bandwidth distribution. Topology is about which restoration path(s) to choose, while the distribution of protection bandwidth determines how much restoration traffic can go through each of the restoration paths. Normally a unit of bandwidth is either in use (working bandwidth) or free (spare bandwidth). In case of a failure, those spare bandwidths are always available for protection purposes, and when it is necessary we can preempt some low priority working traffic and use those bandwidth for restoration purposes as well.

Some systematic categorizations of network protection/restoration methods are given in [13,14]. A network protection/restoration method can be categorized by various metrics, such as whether it is pure restoration or combined protection and restoration, whether it is path or link based. Here we emphasize some key categorizing metrics that will be used throughout this thesis.

- Protection vs. restoration

A network protection/restoration approach is either protection combined with restoration, or totally reactive, as discussed at the beginning of this Section. Pure restoration is basically a 'best effort' approach, and can hardly give any guarantee of performance level. Our work in this thesis is focused on combined protection and restoration, in order to achieve a favorable level of performance.

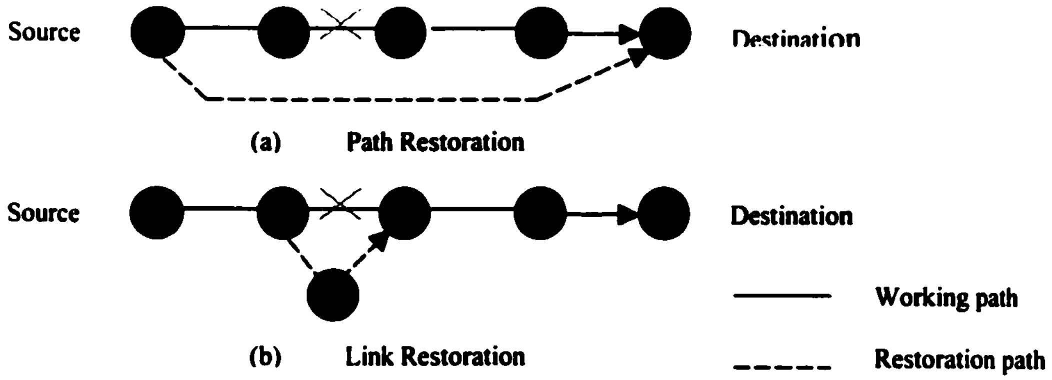


Fig. 1.3 **Path Restoration vs. Link Restoration**

- Path vs. link

A network protection/restoration approach is either path restoration or link restoration based. The difference between path restoration and link restoration (also known as 'span restoration') is shown in Fig. 1.3 (a) and (b) above.

Path restoration is done end-to-end in between the source and destination nodes, while link restoration is done between the two nodes terminating a link (span) cut. Path restoration is more bandwidth efficient since link restoration paths are a subset of all path restoration paths [15]. On the other hand, link restoration is faster since generally it is more 'localized' and involves fewer nodes. Our work in this thesis focuses on link protection/restoration, since restoration speed is one of our major concerns in DWDM layer restoration.

- Shared vs. dedicated bandwidth

A network protection/restoration approach is either based on shared or dedicated protection bandwidths. For example, protection bandwidth is dedicated in 1+1 automatic protection switching [16]. Whereas in N: 1 automatic protection switching [16] one unit of protection bandwidth is shared among N working channels. We prefer to have shared protection bandwidth for sure, under acceptable signaling overhead.

We will discuss further on the issues related to shared vs. dedicated protection bandwidth in Chapter 2. Totally different mathematical models should be used for evaluating network protection approaches, depending on whether protection bandwidth can be shared or not. We will discuss the two different models in Chapter 4 and Chapter 5 respectively.

1.4 Topology Issues in Network Protection

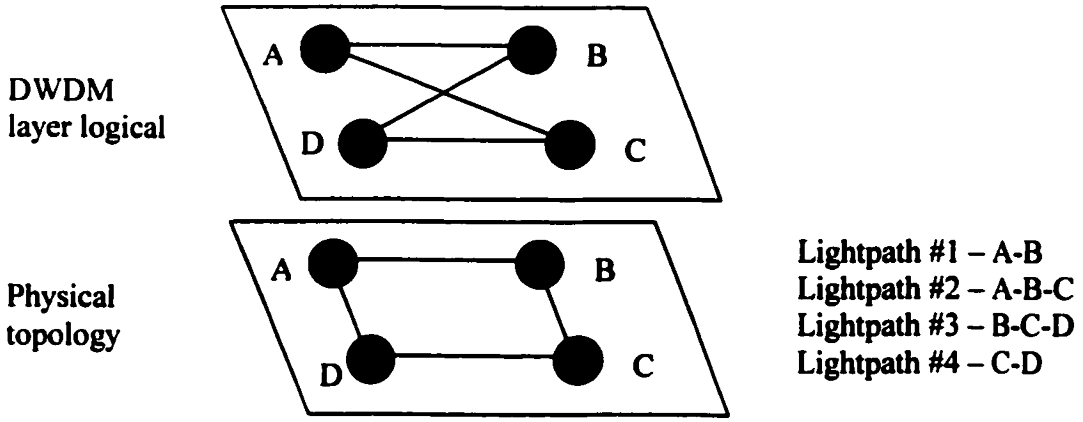


Fig. 1.4 Physical Topology vs. Logical Topology

The topology factor in network protection leads either directly or indirectly towards the selection of restoration path(s) (either path restoration or link restoration). When talking about network topologies, we may refer to either physical or logical topologies (also referred to as 'virtual topology').

A physical network topology is the layout of physical network facilities, including physical fiber spans and optical ADMs/switches/routers. On the other hand, a logical network topology is built on top of a physical topology and seen as a graph representing all the nodes (symbolized ADMs/switches/routers) and logical inter-nodal connections, which may be a WDM channel, an ATM virtual circuit, or a TCP connection. Any topology with shared bandwidth is regarded as a logical topology. At each protocol layer, a logical topology is the 'view' of the network from the next protocol layer above, as depicted in Fig. 1.4.

We know the basic idea of having network protocol stacks is that from bottom to top, layer N provides a certain service and guarantee to layer N + 1. From the topology point of view, the purpose of DWDM layer protection/restoration is to maintain the same DWDM layer logical topology to upper layer protocols (for example, TCP), in case of a fiber cut, or a transmitter/receiver failure for a particular wavelength.

We make further discussions on the physical and logical topologies related to network protection/restoration, in Sections 1.4.1 and 1.4.2 respectively.

1.4.1 Physical Topologies in Network Protection

There are 3 major types of physical topologies for transport networks: physical ring [17-19], physical tree [20,21] and physical mesh [15,22]. Simple physical tree topology such as a binary tree has faded out gradually as a candidate topology for backbone transport networks. This is because in a physical tree there are many singly connected nodes (leaf nodes), and one single physical span cut can isolate a sub-tree totally from the rest of the network [12]. So usually when building survivable transport networks, ring and mesh are the two considerable physical topologies.

There have been debates [12,22] on whether ring or mesh physical topology is better for building survivable optical WDM networks, and those debates are mainly about the tradeoff between restoration speed and bandwidth efficiency. Generally physical ring networks allow for faster restoration but require higher bandwidth redundancy, while physical mesh networks have higher bandwidth efficiency but are comparatively slow in restoration.

1.4.1.1 Physical Ring Networks [17-19]

Self-healing ring (SHR) techniques have already been successfully applied to SONET digital cross-connect (DXC) based systems, which will restore from a node/link failure within about 50 milliseconds. Similarly, WDM-based SHR networks can also be built and achieve fast restoration. WDM SHRs work in the same way as time-division multiplexing (TDM) SHRs, except that the basic unit of bandwidth is not a time slot, but a wavelength. We give an introduction to the operations of various SHRs in Appendix III, where the emphasis is put on the structure and operations of a SHR, without mentioning explicitly whether it is TDM or WDM based.

BLSR/4 (Bi-directional Link-protection Switching Ring) and UPSR (Unidirectional Path-protection Switching Ring) rings belong to the category of physical ring network. In BLSR/4, 4 fibers in total are deployed, 2 working fibers and 2 protection fibers. The working signal is transmitted clockwise and counter-clockwise within two working fibers respectively. Each working fiber is protected by a protection fiber that goes the other way around the ring. In UPSR, 2 fibers in total are deployed, one is for the working signal, while the other is for the protection signal and goes the other way around the ring.

Physical ring networks are favored for their fast restoration. Ring is the simplest survivable network topology, in the sense that each node is of degree 2, which is the bottom line for any protection/restoration to be possible. The simple and symmetric topology of ring networks makes it practical to 'hard provision' restoration paths at the second layer, and thus achieve fast restoration.
Physical ring network topology has some down sides. First of all, ring topology is bandwidth inefficient, since in general half of the total bandwidth has to be reserved in a self-healing ring for protection purposes. Secondly it is usually impractical to connect many cross-connects/ADMs together as a single ring, because of either addressing or optical power budget problems. Thirdly, ring networks cannot be easily scaled [5,8]. Consequently most long haul transport networks are based on physical mesh topologies.

1.4.1.2 Physical Mesh Networks [15,22]

Most backbone (or long haul) transport networks are of physical mesh topologies. We provide the topologies of 2 sample mesh networks in Appendix I, i.e., USA long haul network and France Telecom network. We have found that the average nodal degrees of most backbone transport networks are between 3 ~ 4. In other words, backbone transport networks are usually of sparse mesh topologies. All of the networks we investigate are national SONET transport networks, and it is reasonable to assume that they will be replaced by DWDM networks of the same topologies in the near future.

Mesh networks have higher average nodal degrees than ring networks, which makes higher bandwidth efficiency possible when protection bandwidth can be shared. On the other hand, mesh networks is generally slower in restoration speed than ring networks. There are various proposals on distributed mesh restoration protocols [25,26], but none of them is standardized. Those mesh restoration protocols basically first obtain the restoration path(s) by sending flooding or probing packets upon a network failure, then finish all the required cross-connects along the restoration path(s). The reason why a flooding process is needed is that in legacy transport networks protection/restoration is done at the second layer, which has no knowledge about the network topology and bandwidth resource distribution. Given a general mesh network, restoration can hardly be done within 50 milliseconds (which is a quantitative figure commonly used in SONET networks), by using those mesh restoration protocols mentioned above.

1.4.2 Logical Topologies in Network Protection

There are 3 sub-categories of logical topologies in network protection that are of our research interests: single logical ring networks (built on top of a physical ring network), logical ring cover networks (built on top of a physical mesh network) and P-cycle networks (built on top of a physical mesh network). We cover those 3 sub-categories in Section 1.4.2.1, 1.4.2.2 and 1.4.2.3 respectively.

1.4.2.1 Single Logical Ring Networks

BLSR/2 rings belong to the category of single logical ring networks. The logical operation of BLSR/2 is the same as BLSR/4, except that only two fibers are deployed, and in each fiber the total bandwidth is cut into halves for working and protection signals respectively.

1.4.2.2 Logical Ring Cover Networks

In order to achieve fast restoration in physical mesh networks, a popular approach is to choose multiple logical rings to cover the nodes and links in the mesh network. Each of the rings is configured as a self-healing ring within itself, either TDM or WDM based. Some physical links are traversed by multiple rings, which share the bandwidth on those common links. This is the so-called 'ring cover' approach. Up to now, ring cover is still the most common method to protect physical mesh networks.

Ring cover design is a complicated optimization problem. For example, given a physical network topology and a demand matrix, find a set of rings and a routing pattern that serve all the demands at the minimum total cost [19]. There are many factors to be considered simultaneously in solving such a problem [27]:

(a) The number of rings to use, and the topological layout of each ring,
(b) The logical type of each ring, i.e., UPSR or BLSR,
(c) The capacity allocation of each ring,
(d) The subset of demands to be routed over each ring,
(e) The locations at which demands transit from one ring to another when multiple rings are traversed in end-to-end paths,

...

etc.

The ring cover design methods for SONET TDM networks and optical WDM networks are quite similar, except that a WDM network is a unit capacity network, and the basic unit of bandwidth is a wavelength; whereas in SONET networks, any bandwidth has to be fitted into the standard SONET digital hierarchies, such as OC-3, OC-12.

The objective of ring cover design is usually to minimize the total equipment cost (such as ADMs, cross-connect modules) while serving all the end-to-end demands. Cost differences between good and bad solutions may be millions of dollars or even more [18,19,27].

It is possible to enumerate and compare all the planning alternatives in solving the ring cover problem, when the network is small. But as the number of network nodes and links increases, the number of decision variables also increases rapidly, and the problem becomes combinatorially explosive. So usually in order to reduce the complexity, the whole ring cover problem is divided into 2 independent sub-problems: ring finding and ring planning [18,19,27]. There are many algorithms available for solving each sub-problem.

(a) Ring finding algorithms

Algorithms in this sub-problem consider the whole physical mesh network as a connected graph, and try to find a set of rings to cover all the links that active traffic passes through.

There are various ring finding algorithms, some of them are classical methods, which pick out all the rings exhaustively from a network graph. Most classical algorithms belong to one of the following four classes: circuit vector space [28-30], backtracking algorithms [28,31], powers of adjacency matrix [28] and edge-digraph [28]. The fastest known classical method is Johnson's [31], which is a backtracking-based method with time complexity O (n + e)(c + 1), where e is number of links in the network, n is number of nodes in the network, and c is the number of rings in the network.

In addition to classical methods, which are exhaustive, there is another category of ring finding methods based on heuristics, such as ring node routing [32], Eulerian graph decomposition [33] and K-shortest path based ring-finding [41]. There is no guarantee that all the designated nodes/links are covered. However, the heuristics can run faster than classical methods and yield good node/link coverage in most cases.

(b) Ring planning algorithms

Algorithms in this sub-problem are based on the ring set found in sub-problem #1, and they determine issues such as the logical type and capacity allocation of each ring, the subset of demands to be routed over each ring, the locations of inter-ring transition. These algorithms are either linear programming (LP) or heuristic based [18,19,24]. Note that even if a ring planning algorithm is based on LP, we can hardly say that it can find the absolute optimum planning scheme. This is because the cost model of each LP formulation only reflects some major aspects of the real world network costs. On the other hand, absolute optimum is not quite desirable in ring planning as an engineering problem. We would adopt a planning scheme as long as it is cheaper than most others.

In summary, the mesh network ring cover approach tries to protect a physical mesh network with a set of logical self-healing rings. That is not really an elegant approach, since as we have already discussed, ring cover is a very hard problem to solve. There are also some practical disadvantages with ring cover in engineering implementation, which will be discussed at the end of Chapter 4. But ring cover will still be the most popular approach for mesh network protection/restoration at the second layer, before a better mesh protection/restoration method comes into reality.

1.4.2.3 P-cycle Networks

Some interesting research has been done on network protection with a special ring/cycle topology called protection cycle, or P-cycle for short [22,23]. A P-cycle topology consists of a ring and all the links that are straddling the ring (chordal links). The new idea is that those straddling links can be protected by a pair of node-disjoint paths that go opposite ways around the ring.

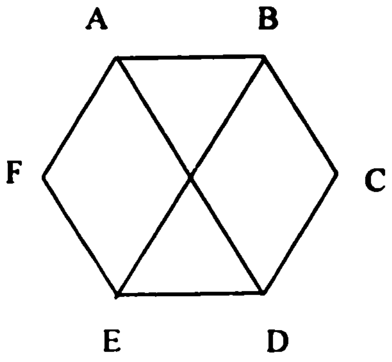


Fig. 1.5 **P-cycle Topology**

The idea of so-called 'P-cycle' topology is shown in Fig. 1.5 above. Suppose that there is one unit of working bandwidth on each of the links in the network, and there is one unit of spare bandwidth on each of the links along ring ABCDEFA. If any on-cycle link fails, say link A-B, by carrying on link protection along path A-F-E-D-C-B, disrupted traffic on link A-B can be restored. Furthermore, if a straddling link fails, say link A-D, we have 2 protection paths A-F-E-D and A-B-C-D along the ring. Similarly if B-E fails, we have 2 protection paths B-C-D-E and B-A-F-E along the ring. In this way we can protect more traffic than the traditional self-healing ring approach, by making use of the connectivity in between ring nodes.

We can quantify the protection efficiency of a given P-cycle topology by its 'score' [22,23], i.e., number of link protection paths it provides per unit of spare bandwidth consumed:

Score = (number of on-cycle links + number of straddling links) / number of on-cycle links

In other words, since protection bandwidths are already available on those on-cycle links, the more straddling links, the higher is the total protection efficiency.

In a way P-cycle can be regarded as the compromise between pure ring and mesh topologies. It has been proved that the P-cycle topology is more efficient than any other topological patterns such as trees, in terms of number of link protection paths provided per unit of spare bandwidth consumed [34]. It has been further proved that the P-cycle topology has the same upper bound of average working/spare bandwidth ratio as a general mesh network, for 100% link restoration [34].

Since it is more bandwidth efficient to use a logical ring as a P-cycle instead of as a pure ring, one may ask what if we use a set of P-cycles to cover and protect mesh networks. That will be addressed in Chapter 4, as one of our objectives in this thesis.

1.5 Motivations

From the above discussions on topology-related issues in network protection, we believe that the P-cycle topology can leverage the tradeoff between restoration speed and bandwidth efficiency, and is a promising choice for link protection/restoration in physical mesh networks. Based on the theoretical studies so far on P-cycle protection/restoration, we want to address the feasibility of P-cycle protection/restoration in two different types of mesh WDM networks: static optical WDM networks and wavelength routing networks.

Our general interest in this thesis is on network protection/restoration at the DWDM layer, with ring/cycle topologies. From our previous discussions, in trying to protect backbone mesh DWDM networks with ring/cycle topologies, the following topics are worth studying.

There are many recent publications on WDM network protection/restoration that try to give a 'comprehensive' solution for optical WDM networks in general. As discussed in Section 1.1, there are two categories of switching equipments for optical WDM networks: plain optical switches and wavelength routers. Network protection/restoration has to be done differently when using different switching equipments, and the mathematical models for evaluating protection/restoration methods should also be different. Unfortunately little attention has been paid upon this issue.

As we learn from classical ring enumeration algorithms in Section 1.4.2.2, the number of rings/cycles in a network graph increases exponentially as the number of nodes and links increases. That is a serious scalability problem in engineering. So we are still looking for a novel ring-finding method, which is able to find a set of rings/cycles to cover all or most links in a network, while the number of rings/cycles increases linearly with the number of links.

Some preliminary studies have been done on network protection/restoration with the P-cycle topology. Since P-cycles are more bandwidth efficient than pure rings, a naturally asked question is: would it be beneficial if we use P-cycles instead of pure rings, in the ring cover approach for mesh WDM networks?

Traditionally ring cover is the only way ring topology is used in mesh network protection/restoration. As wavelength routing networks are becoming reality, it will be interesting to see whether we can use rings/cycles in a distributed protection/restoration protocol, as part of the scalable WDM layer. Until now there are very few articles on distributed ring/cycle based network protection.

1.6 Objectives

The general objective of this thesis is to investigate backbone mesh DWDM network protection/restoration with ring/cycle topologies, in particular P-cycle. Specifically we want to:

1) clarify the differences between the protection/restoration models in two different optical WDM networks, namely static WDM networks with plain WDM switches and wavelength routing networks with wavelength routers respectively.

2) propose an algorithm that is able to find a scalable set of link covering rings, in a sparse mesh network. Study the performance of this algorithm.

3) find a mathematical model to compare the performance of pure ring cover and P-cycle cover in static WDM networks.

4) investigate methods for the protection/restoration of wavelength routing networks by ring/cycle topologies.

1.7 Methodologies And Approaches

There are a few general methodologies in achieving our objectives:

Network modeling and assumption

In a real world WDM network, the performance of a protection/restoration method is influenced by many factors, such as the wavelength capacity of each link, and the distribution of working/spare wavelengths across network links. We need to make some reasonable modeling and assumptions on these operational factors, so that the network protection/restoration problem could be further tackled mathematically. We shall put forward our model on nodes, links and wavelength distribution.

Decoupling topology factor from traffic distribution factor

There are always two fundamental factors involved in network protection/restoration issues: topology and protection bandwidth distribution. First of all, these two factors are related to each other. For example, a restoration path is feasible only when all the links along the path are active and there is enough protection bandwidth along the path. If there is a failed link along the restoration path, there is no point talking about the protection bandwidth distribution along the path. On the other hand, dealing with those two factors altogether usually makes the whole problem very complicated. So in this thesis, we adopt a common practical approach: decouple the two factors from each other, i.e., consider the topology factors first, and then study the impact of protection bandwidth distribution over those fixed topologies. The division of ring cover problem into two sub-problems is a good example of such a practical approach. Another example can be found in the so-called static routing and wavelength assignment problem (RWA) [37], where people choose a set of paths first, then try to push as much traffic as possible through those pre-chosen paths.

Graph-theoretical and algorithm analysis

We need to carry on graph-theoretical analysis on a network graph when trying to find a set of link covering rings. We shall consider important topological factors such as the nodal degree of a network, connectivity, node-disjointness and link-disjointness between a pair of paths. A lot of our work in this thesis will be based on the analysis on various algorithms that are already available. For example, the ring-finding algorithm we propose in Chapter 3 is based on proven algorithms [16,41] for finding node/link disjoint paths in a network graph. Similarly, in solving the Maximum Rerouting Flow (MRF) problem in Chapter 5, we first look at labeling algorithm [43] and flow augmenting path algorithm [40] that are designed for general network flow problems, then we start investigating our own approaches because those two algorithms do not fit into our network model.

Simulation approach

We will use this approach mainly to deal with the protection bandwidth distribution factor. Because the performance of a network protection/restoration method fluctuates as the protection bandwidth distribution changes over the pre-chosen restoration path(s), we shall obtain the statistical performance of a certain network protection/restoration method by running simulations implemented in C/C++ language.

Linear programming (LP) for algorithm/protocol evaluation

As it turns out, many network protection/restoration models (such as the maximum rerouting flow in Chapter 5) have linear objective functions and linear constraints. Therefore, we shall use linear programming (LP) to evaluate our algorithms and protocols. By using and solving the linear programming formulations of those models, we get the theoretical optimum of a certain network protection/restoration method. Even if for some reasons we cannot do that well in practice, those optimum results are still valuable for evaluation and comparison purposes.

We shall use Ilog CPLEX 7.0 [45], a popular linear programming software package as our tool. With the C++ libraries provided by CPLEX 7.0, it is very convenient to build and solve linear programming models.

1.8 Contributions And Thesis Organization

The following are the contributions of this thesis.

Based on analyses on the way plain WDM switches and wavelength routers work, we come up with the viewpoint that protection bandwidth can be shared at the DWDM layer in wavelength routing networks. While in static WDM networks, protection bandwidth cannot be shared at the DWDM layer.

We have proposed and formulated the Straddling Link Algorithm (SLA), a novel ring finding algorithm that can find a small set of rings to cover all or most links in a sparse mesh network. The algorithm is coded in C language, and the performance of the algorithm has been evaluated.

We have proposed and implemented a generic linear programming formulation based on the SLA ring set, and used it to compare the methods of pure ring cover and P-cycle cover in static WDM networks.

We have proposed and evaluated a distributed ring/cycle protection/restoration protocol for wavelength routing networks, based on the distributed version of the Straddling Link Algorithm. The ring-based protection/restoration protocol performs very close to the theoretical optimum under our network modeling assumptions. The favorable performance of the protocol justifies that P-cycle is an efficient topology for link protection/restoration in mesh networks.

This thesis is organized as follows:

In Chapter 2, we discuss on the differences between static WDM networks and wavelength routing networks, which lead to major differences in their protection/restoration methods and models. Some network modeling assumptions for those two categories of optical WDM networks are also given in this chapter.

In Chapter 3, we introduce the basic ideas, details and performances of a brand new ring finding heuristic in sparse mesh networks. The ring set found with the so-called 'straddling link heuristic' covers most links in a sparse mesh network, with a scalable number of rings.

Chapter 4 introduces a generic linear programming model, which is used to make relative comparisons between the protection/restoration performances of different ring sets in static WDM networks. Discussions have been made on the simulation results from sample networks.

Chapter 5 introduces a distributed ring-based protection/restoration protocol for wavelength routing networks. The protocol performs very close to the theoretical optimum, and there is only moderate overhead implementing the protocol within the WDM layer.

Chapter 6 gives some design guidelines and operational experiences.

Chapter 7 presents the concluding remarks.

Chapter 2

Network Modeling and Operation for Protection Analysis

In this chapter, we present the network model and operation used in the rest of the thesis. As discussed in Section 1.1, there are two basic types of optical WDM networks: static WDM networks and wavelength routing networks, which are comprised of plain optical switches and wavelength routers respectively. Section 2.1 addresses the differences in the way network protection/restoration is done in two different types of optical WDM networks. Section 2.2 gives some network modeling assumptions to be used for those two types of optical WDM networks.

2.1 Protection/Restoration in Static WDM Networks and Wavelength Routing Networks

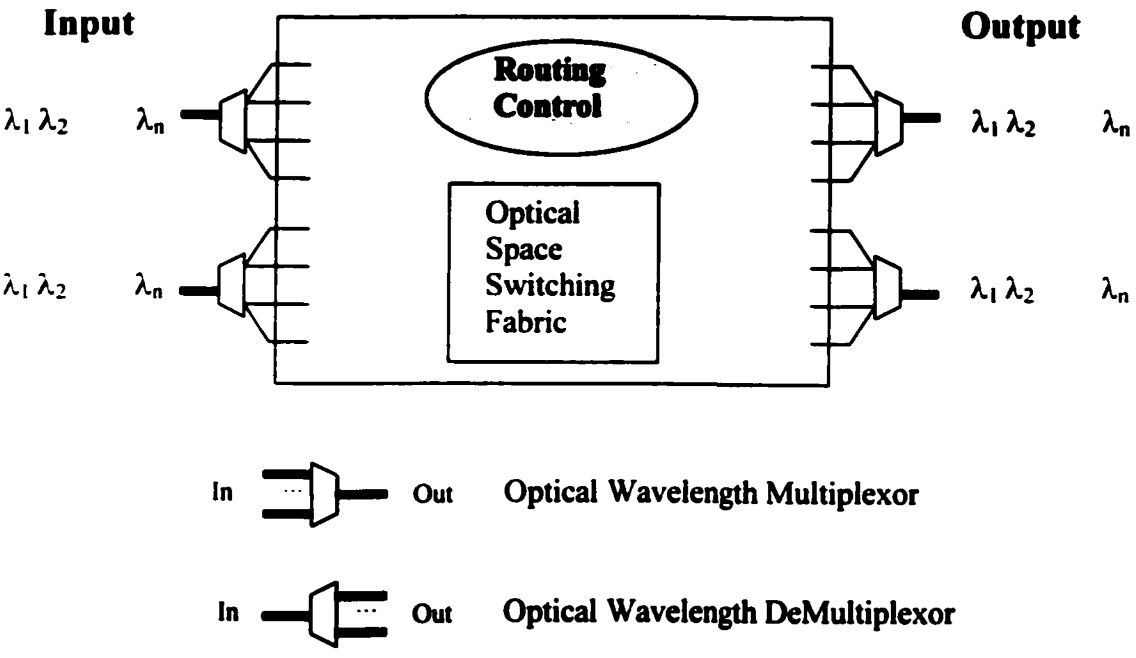


Fig. 2.1 Generic Architecture of An Optical Lambda Switch

Fig. 2.1 depicts the generic architecture of an optical lambda switch. Every optical lambda switch has an optical space switching fabric, which switches optical signal from input ports to output ports (or from input wavelengths to output wavelengths). In the case of a plain optical lambda switch, it doesn't have a routing control module, and the mapping between input ports and output ports is setup manually by a human network operator. A type of more intelligent WDM switch called 'wavelength router' is also emerging. In this device, the input port to output port mapping is decided by the routing control module in order to serve the bandwidth requirement of layer 3 without human intervention.

2.1.1 Protection/Restoration in Static WDM Networks

We consider a static WDM network consisting of plain optical lambda switches. Each optical switch is only aware of its direct adjacent neighbors, and has no idea about network layer information, such as network topology and the distribution of working/spare wavelengths over network links. Thus an end-to-end lightpath has to be setup manually via a network management system, and the network operator has to specify every intermediate optical switch along the lightpath. From another respect, this kind of WDM network can only accommodate end-to-end demands that are permanent or semi-permanent. Our static WDM networks are still transport networks with no third layer intelligence, although network throughput has been boosted dramatically over traditional SONET networks by the introduction of optical lambda switching.

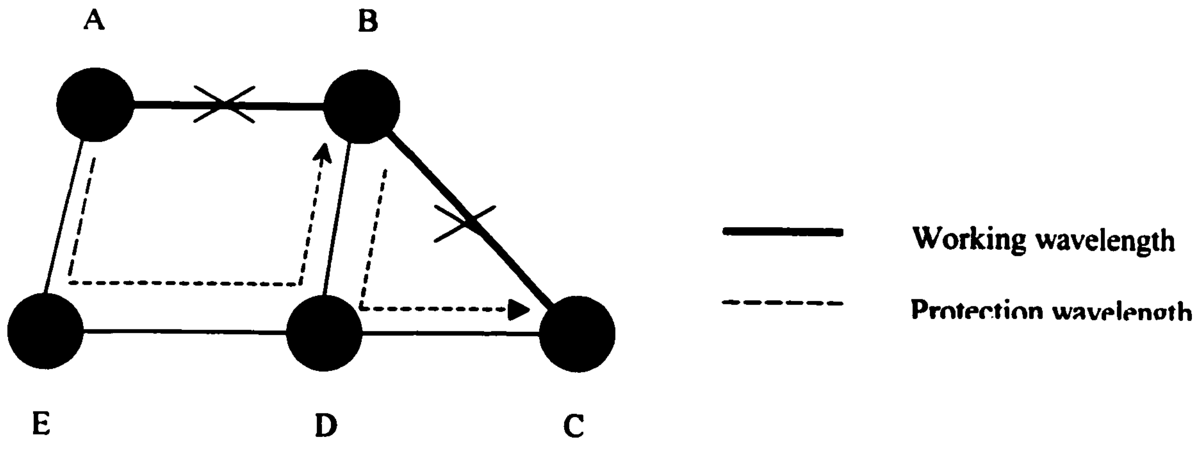


Fig. 2.2 **Protection Bandwidth in a WDM Ring Cover Network**

Consequently, in static WDM networks that are covered and protected by a set of logical self-healing rings, protection switching has to be set up in a preventive way, through a set of 'hard provisioning'. Protection bandwidth can only be shared within a ring itself, in a point-to-point manner. That is illustrated by a simple example in Fig. 2.2 above.

In the simple WDM ring cover network example in Fig. 2.2, there is an active demand of one wavelength goes along path A-B-C. The whole path A-B-C is covered and protected segment by segment by two rings A-B-D-E and B-C-D, which are of UPSR logical type (mentioned in Appendix III). If link A-B fails, protection switching will be done along A-E-D-B. Similarly if link B-C fails, protection switching will be done along B-D-C. Now the question is that under the assumption that only one link failure may occur at a given time, whether we can we install only 1 unit of protection wavelength on link B-D (the common link of the two rings) to accommodate both rings. The answer is negative, and we still have to install 2 units of protection wavelengths on link B-D. Because in order to share protection bandwidth between two rings, node B and D have to keep track of the statuses of both rings, i.e., which one is in normal state and which one is in protection switching state. Such an inter-ring coordination may be possible for the simplest case in Fig. 2.2 where there is only one common link shared by a total of two rings, except that the saving in protection bandwidth is not worth the signaling overhead and increased complexity of the optical switches/OADMs. In a general WDM ring cover case where there are many rings, which overlap with each other here and there, protection bandwidth sharing between rings is generally a network layer coordination, and thus beyond the capabilities of plain optical switches.

2.1.2 Protection/Restoration in Wavelength Routing Networks

As opposed to plain optical switches, wavelength routers collect network layer information both periodically and upon occurrence of any topology/wavelength distribution change, via either an in-band signaling channel (e.g., a particular field in a information packet) or an out-of-band signaling channel (e.g., a dedicated wavelength). Each wavelength router thus has a local image of network topology, distribution of working/spare wavelengths on each link. WDM networks comprised of wavelength routers are referred to as 'wavelength routing networks'. In a wavelength routing network, end-to-end lightpaths can be setup automatically by the wavelength routers, once the source node, destination node and bandwidth requirement are specified. Therefore in such a WDM network, end-to-end lightpaths can be setup and torn down at a regular basis, without much provisioning and maintenance overhead. Plain optical WDM switches will be commercially available first, but wavelength routers will enable intelligent and scalable transport networks, which is the ultimate trend of broadband network development.

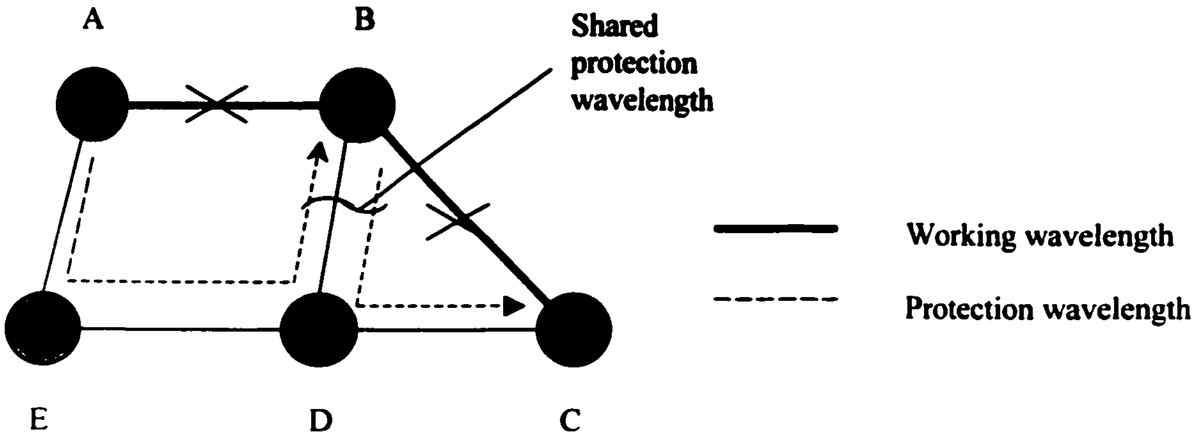


Fig. 2.3 **Protection Bandwidth in a Wavelength Routing Network**

Network protection/restoration in wavelength routing networks is quite different from that in static WDM networks. Upon a physical span/link failure, disrupted traffic is rerouted at the WDM layer, according to the local databases at related nodes about network topology/wavelength distribution. As opposed to the protection switching in static WDM networks, which is done at the second layer, rerouting in wavelength routing networks is done at the so-called 2.5th layer [6], and protection bandwidth can be shared therein because of the awareness of network layer information. That notion is depicted in Fig. 2.3 above. The network topology and traffic distribution are the same as in Fig. 2.2, except that each node here is a wavelength router. Now under the same assumption that only one link failure may occur at a given time, we can install 1 unit of protection bandwidth on link B-D to accommodate both link A-B failure and link B-C failure. For example when A-B fails, node A will find out a feasible rerouting path A-E-D-B from its local database, and then reroute the traffic along A-E-D-B when it is setup. Because node A has a local image of network topology and wavelength distribution, it is able to make independent decisions on what to do upon link A-B failure.

In summary, 'ring/cycle topologies' has different meanings in two kinds of WDM networks. In static WDM networks, a ring is a logical self-healing ring to carry on protection switching upon a failure. Protection bandwidth cannot be shared between different rings. On the other hand, in wavelength routing networks a ring/cycle is a topological pattern to find rerouting paths, as will be discussed in Chapter 5. Protection bandwidth can be shared between different rings in wavelength routing networks, under the assumption that only one link failure may occur at a given time.

As a result, although we use network restorability as the metric to evaluate the protection algorithms/protocols for both kinds of networks, their mathematical formulations are totally different depending on whether protection bandwidth can be shared or not. We will discuss further on the different protection/restoration approaches for two different kinds of WDM networks in Chapters 4 and 5 respectively.

2.2 Network Modeling and Assumptions

In order to tackle the network protection issues in a mathematical way, some simplifications and assumptions are needed. We partition those simplifications and assumptions into five parts: modeling of network nodes and links, modeling of wavelength distribution, modeling of wavelength routing & distribution protocols, modeling of network failures and modeling of wavelength conversion. All these modeling features apply to both types of WDM networks in this thesis, except wavelength routing & distribution protocols, because they are specific to wavelength routing networks.

(1) Modeling of nodes and links:

We represent a mesh WDM network by a graph comprised of a number of nodes and links. Each node represents either a plain optical switch or a wavelength router, depending which kind of network is being addressed.

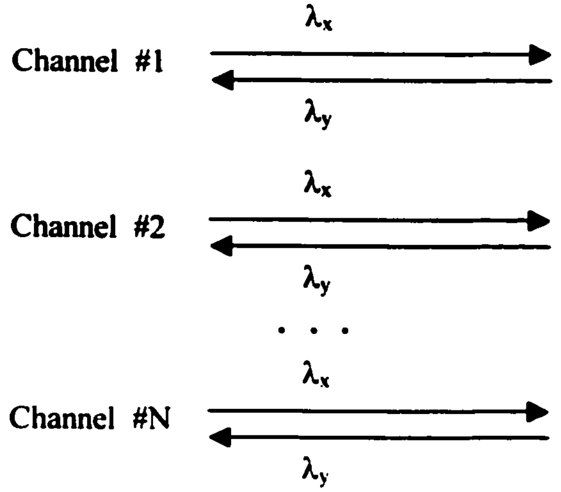


Fig. 2.4 **Link Model**

A 'link' in our network graph is actually a physical span, within which there may be multiple fibers running in parallel between two end nodes. We assume that each end-to-end traffic demand is served by a pair of bi-directional lightpaths, and those two lightpaths take the same route. We also assume that on each link, there are N pairs of bi-directional wavelengths, as shown in Fig. 2.4 above. For simplicity, in subsequent discussions we shall use a statement like 'there are 10 working wavelengths and 2 spare wavelengths on a link', instead of saying 'there are 10 pairs of bi-directional wavelengths in use and 2 pairs of bi-directional wavelengths free on a link'.

Note that N (e.g. #12) is just a hard coding on the capacities of all the physical spans. In practice, the capacities of all the physical spans in a DWDM network are not necessarily the same. Also with the development in DWDM techniques, 64 wavelengths per fiber is quite a normal arrangement. However as it will turn out in Chapter 4 and Chapter 5, the mathematical models for network protection/restoration analysis are all linear. Changing the absolute value of the capacity of each link doesn't affect the network-wise restorability. Instead what matters is the relative ratio of working over spare wavelengths on each link, and network-wise.

(2) Modeling of wavelength distribution:

The number of working and spare wavelengths on each link is the result of the routing of end-to-end demand pairs. Since we do not have real world traffic data for the performance evaluation of our sample networks later on, we shall assume that the number of spare wavelengths on each link follows a normal or uniform distribution, and the number of spare wavelengths on different links is independent of each other. That may not lead to a 100% realistic traffic distribution, but on the other hand it is also an approach independent of any particular traffic patterns, thus enabling us to analyze network protection/restoration without a loss of generality.

There are some special considerations we make in dealing with the traffic distribution factors. The sample networks we investigate are all sparse mesh networks of average nodal degree around 3. It has been proved that to achieve 100% link restorability in a network, the upper bound on the ratio of network-wise working/spare bandwidth is d – 1, where d is the average nodal degree [15]. So for our sample networks, that theoretical upper bound is around 2, which means that in a network of average nodal degree around 3, the average ratio of working/spare bandwidth on each link (as well as network-wise) should be less than 2 to achieve 100% link restorability.

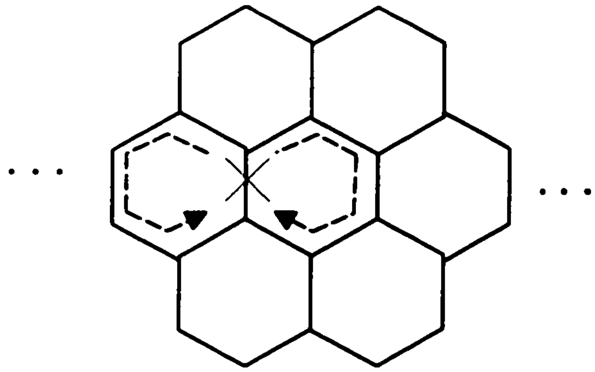


Fig. 2.5 **100 % Link Restorability Under Ideal Conditions**

In Fig. 2.5 above, we give an example to show the perfect combination of network topology and bandwidth distribution to achieve that theoretical upper bound. The network in Fig. 2.5 has a cellular topology, and the nodal degrees of the central nodes are all equal to 3. On each link, there are 2 units of working bandwidth, and 1 unit of spare bandwidth. If one of the links fails, all the working traffic can recovered be by link restoration. In a real world mesh transport network, we can hardly do that well with the combination of real topology and bandwidth distribution factors. So in our simulation studies, we are interested in observing the restorability performance under such a condition, where network-wise ratio of working/spare wavelengths goes between 1 ~ 2. Note that 100% bandwidth redundancy is the figure required by ring networks to achieve 100% restorability.

(3) Modeling of wavelength routing and distribution protocols [5,8]:

In the architecture of dynamic wavelength routing networks there are two key protocols: wavelength routing protocol and wavelength distribution protocol. With the wavelength routing protocol, any change in optical wavelength resource in each fiber link is flooded through the whole network, and trigger each node to update its network resource database accordingly. On the other hand, the wavelength distribution protocol signals the setup and teardown of an end-to-end lightpath. These two protocols are derived from mature architectures (such as OSPF and LDP) and expected to be comparatively straight forward, yet they are still in prototyping stage and not commercially available. In Chapter 5 we will make discussions on the rerouting in wavelength routing networks, and for all those discussions we assume that the wavelength routing and distribution protocols are up and running, such that each node knows the topology of the whole network as well as the wavelength resource on each link, and is able to request a lightpath to another node when needed.

(4) Modeling of network failures:

In a real world WDM network, various failures may occur such as node failure, physical span failure, interface card failure and single wavelength channel failure. For critical equipments like backbone WDM switches/routers, there are usually built-in backup modules as well as backup power supply, in order to prevent a whole node failure from happening. An interface card failure is equivalent to single or multiple wavelength channel failures, which is a subset of a physical span failure. Therefore we shall focus on the protection against single physical span failures, which happen most often in real world networks. We assume that at a given time, only one physical span failure may occur.

(5) Wavelength conversion:

We assume that full wavelength conversion is available on each WDM switch/router, whenever needed. In other words, we care only about wavelength availability in lightpath setup, protection switching or protection rerouting, instead of the wavelength continuity. Full tunable wavelength converters [1,3] are still rather expensive components nowadays, but by making such an assumption, the studies on network protection/restoration become much easier.

2.3 Concluding Remarks

We have discussed two different types of optical WDM networks in this chapter, and come up with the argument that protection bandwidth can only be shared at the DWDM layer in wavelength routing networks. Whether protection bandwidth can be shared makes major differences in the mathematical models to evaluate protection/restoration performances, as will be presented in Chapter 4 and Chapter 5 respectively.

Chapter 3

Straddling Link Algorithm: A Ring-finding Heuristic

In this chapter, we put forward a novel method to decompose a network graph into a set of link-covering rings. We impose neither a strict objective nor any strict constraints in ring finding, because we see the ring-finding problem in network protection/restoration as an engineering problem, as opposed to a strict mathematical problem. We deem a ring-finding algorithm acceptable as long as the resultant ring set meets the following criteria:

1. Covers most links in the network.
2. Number of rings increases linearly in terms of network links (scalable).
3. Each ring should not contain too many nodes, or else we may end up with either an infeasible self-healing ring or an infeasible rerouting path.

A link is covered if it is either an on-cycle link or a straddling link in the ring set found. Generally in the process of ring finding, we prefer to choose those rings that have straddling links. In fact our ring finding method is just based on searching for ring-straddling links. It is a heuristic approach because there is no guarantee that all the links in a given network graph will be covered, although the algorithm achieves a good link coverage performance in most networks tested.

3.1 Basic Ideas of the Straddling Link Algorithm

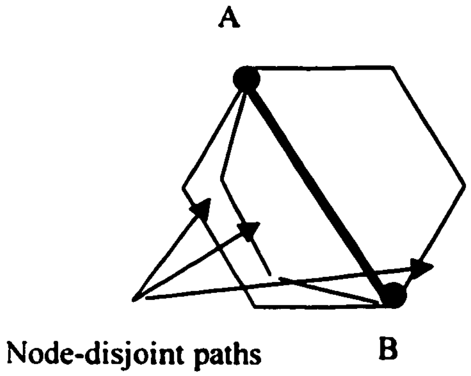


Fig. 3.1 Finding a Ring by Combing Two Node-disjoint Paths between A and B

A ring can be regarded as made up of two node-disjoint paths. Furthermore, we can regard a P-cycle as made up of two node-disjoint paths between the two end nodes of a straddling link, as shown in Fig. 3.1. Note that the nodal degrees of both end nodes of a straddling link are greater than or equal to 3. That is the fundamental idea of our straddling link algorithm.

Suppose we are given a general mesh network G = G (V, E), where V is the set of network nodes, and E is the set of network links. Before finding a set of link covering rings, we can always prune off those nodes of nodal degree 1 and the links connected to them, because no ring can cover such nodes and links. Then we can classify the following link restoration cases for the remaining network links.

1) Case of nodal degrees ≥ 3 for both end nodes; there are 3 sub-cases of protecting a failed link by using the extra paths available for restoration.

   (a) There are at least 2 node-disjoint paths between nodes A and B, as shown in Fig. 3.2.

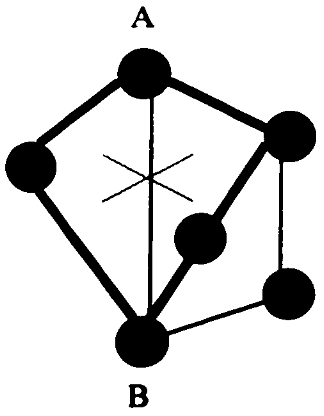


Fig 3.2 **Case 1(a)**

   (b) There is one or more paths between nodes A and B, but none of them is node-disjoint, because there is at least one node common to each restoration path. This is shown in Fig. 3.3.

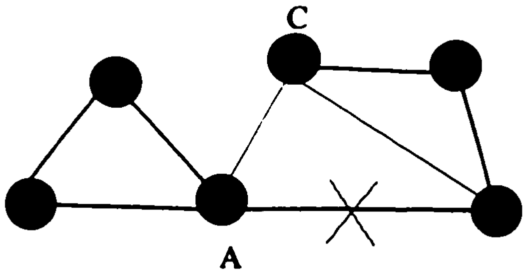


Fig. 3.3 **Case 1(b)**

(c) There is no path between nodes A and B, because the failed link A-B is a cut edge, as shown in Fig. 3.4.

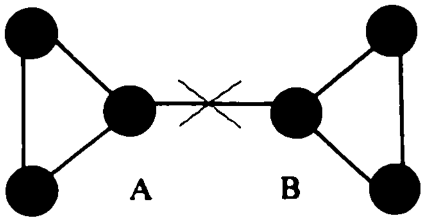


Fig. 3.4 **Case 1(c)**

2) Case of the nodal degree of at least one end node = 2; there are 2 sub-cases of protecting the failed link.

(a) There is one or more paths between nodes A and B, but none of them is node-disjoint, because the other link adjacent to the node of degree 2 is common to each restoration path. This is shown in Fig. 3.5.

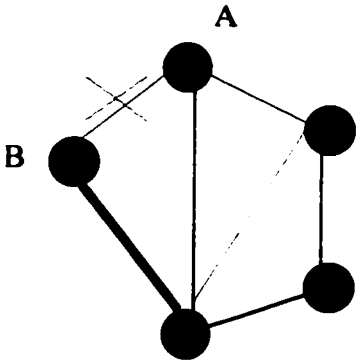


Fig. 3.5 **Case 2(a)**

(b) There is no path between nodes A and B, because the failed link A-B is a cut edge, as shown in Fig. 3.6.

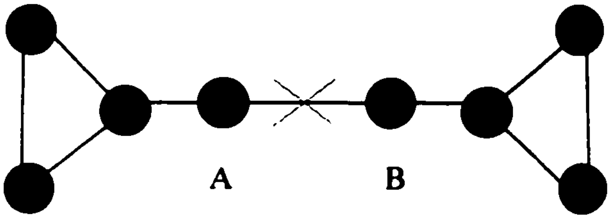


Fig. 3.6 **Case 2(b)**

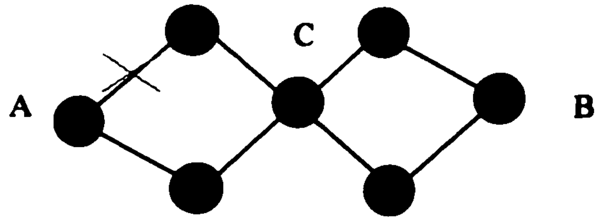


Fig. 3.7 **Two Link Disjoint Paths Between A & B Form An '8' through Node C**

Note that the reason we emphasize on node-disjointness of the restoration paths is that two link-disjoint paths are not necessarily node-disjoint, but two node-disjoint paths are automatically link-disjoint. Fig. 3.7 above shows two link-disjoint paths forming a 'figure 8' through the same node C, which implies a rerouting path may traverse node C twice in case of a link failure. This is not allowed in either self-healing ring protocols or most network layer routing protocols.

In summary, we can cover a link in Case-1a with a ring formed by the second and third shortest node-disjoint paths between nodes A and B (the first shortest path is the straddling link to be protected). Actually only those links of Case-1a can be covered as a ring straddling link. We can also cover a link in Case-1b or Case-2a with a ring formed by the link itself and the second shortest node-disjoint path between nodes A and B. But we can never cover a link in Case-1c or 2b with a ring.

3.2 Details of the Straddling Link Algorithm

Based on the discussions above, we can now propose our ring finding heuristic. The flow diagram of the straddling link algorithm is presented in the following.

From Fig. 3.8, we can see that for each link in Case-1a, we form a ring by combining the second and third shortest node-disjoint paths between two end nodes. For each link in Case-1b form a ring by combining the link itself and the second shortest node-disjoint path. We are trying to cover the links in Case-2a with the ring set previously found to cover Case-1a and Case-1b links. Because this algorithm is based on the iterative execution of shortest path algorithm between the two end nodes of those links, whose two end nodes are of degree >=3, i.e., in between the two ends of potential straddling links, we name this algorithm 'straddling link' algorithm.

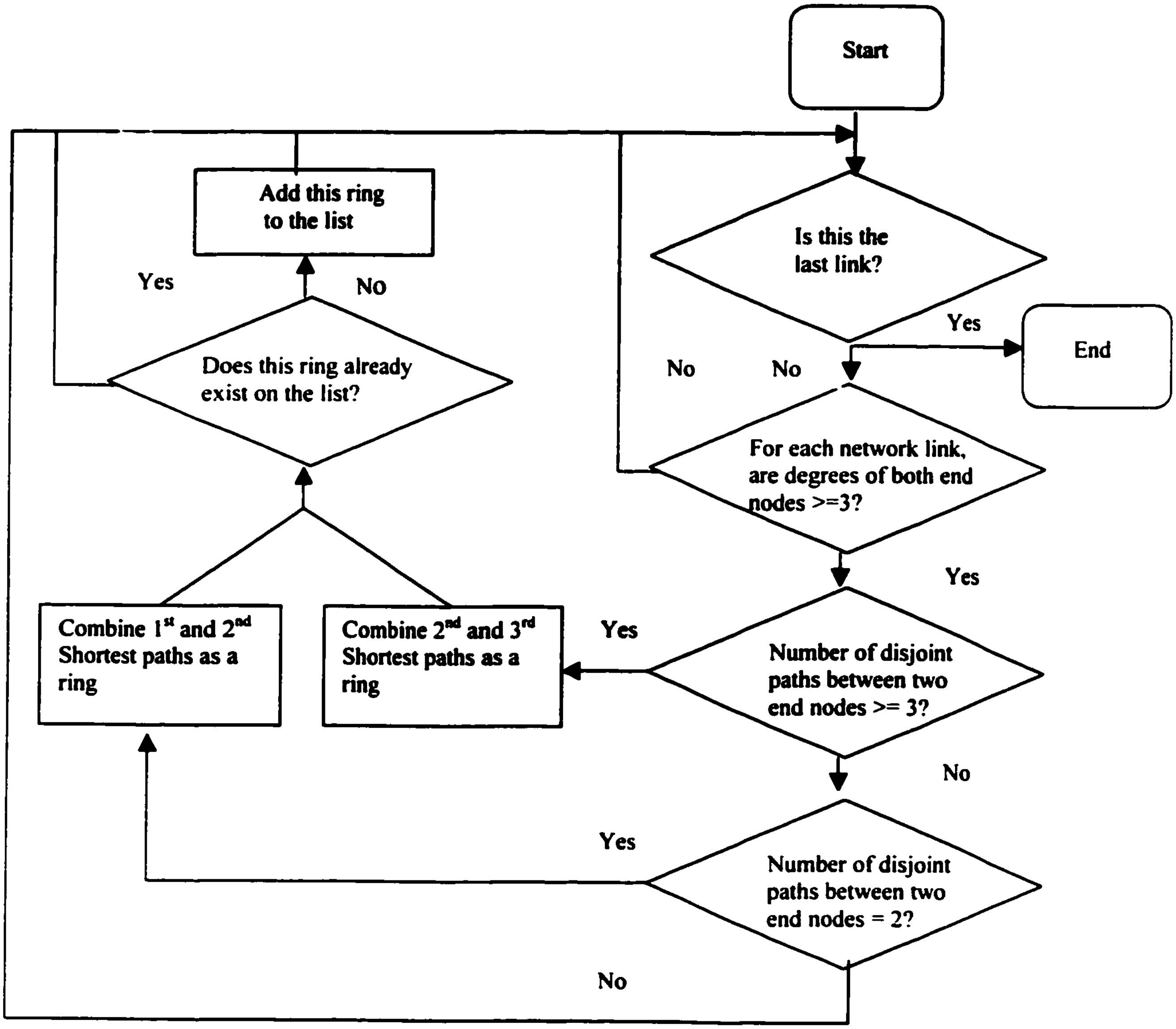


Fig. 3.8 Flow Chart of the Straddling Link Algorithm

The iterative shortest path calculation is based on Dijkstra's algorithm using a binary heap. Details of binary heap implementation of Dijkstra's algorithm can be found in Appendix IV. The basic idea is to maintain the temporarily labeled nodes and their temporary distances in a binary heap data structure, and go through the procedures of Dijkstra's algorithm by a set of basic heap operations. That is, insert a temporary node, decrease the distance of a temporary node, and delete the node of minimum temporary distance. The time complexity of each of the above operations is O (logN), where N is number of network nodes, and log N is actually the average depth of the binary heap. The overall time complexity of finding a path with heap-Dijkstra is therefore O(NlogN).

To guarantee the disjointness of the paths between two nodes by iterative executions of Dijkstra's algorithm, the path previously found needs to be marked in a certain way before we proceed to find the next path. We adopt two similar ways to implement the path marking: node-disjoint marking and link-disjoint marking, as shown in the pseudo codes below.

```
Node-disjoint Marking Algorithm
begin
        if pred(node B) = node A
                l := find_link(node A, node B);
                l.distance := INFINTE;
        end;
        else
                i := pred(node B);
        do
                        for each link l adjacent to i
                                l.distance := INFINITE;
                        end;

                        /* back-tracing one hop along the path */
                        i := pred(i);

                while i ≠ node A
        end;
end;
```

Fig. 3.9 Pseudo Codes of Node-disjoint Marking Algorithm

```
Link-disjoint Marking Algorithm
begin
        i := node B;
        do
                l := find_link(i, pred(i));
                l.distance := INFINITE;

                /* back-tracing one hop along the path */
                i := pred(i);

        while i ≠ node A
end;
```

Fig. 3.10 Pseudo Codes of Link-disjoint Marking Algorithm

The basic idea for both path-marking algorithms is to denote one end node of the path as the source and the other end node as the destination. We then backtrack from the destination node to the source node along the path, and mark the distances of all the intermediate links to infinity so that they will not be picked up by later iterations of Dijkstra's algorithm. Node-disjoint marking marks all the links adjacent to each intermediate node along the path, while link-disjoint marking only marks those links along the path.

The difference between those two path-marking algorithms is that node-disjoint marking will guarantee the node-disjointness among paths found, thus any two paths can be combined as a simple ring. On the other hand, the combination of the second and third shortest paths with link-disjoint marking may not be a simple ring, in that case the merged ring will not be added to the final ring set. Using either path-marking algorithm, each newly formed ring is checked to see if it already exists on the current ring list. If it does, it will not be added to the ring list as a duplicate.

3.3 Performance Evaluations

The number of rings found by the straddling link algorithm is upper-bounded by the number of links is the network. Because in a real world network, there are usually some nodes of degree 2, thus only part of the links are of type 1a or 1b; and for each link of type 1a or 1b, only one ring is yielded, if it is not a duplicate. For each link of type 1a or 1b, Dijkstra's algorithm will be iterated for 3 times at most. The complexity to find the first shortest path (the link itself) is O(1), while the complexity to find the second or the third shortest path is $O(N\log N)$ (see discussion of binary heap implementation of Dijkstra's algorithm in Appendix IV). So the complexity for each link of type 1a or 1b is: $O(1) + O(2N\log N) = O(N\log N)$. Finally, the total time complexity of straddling link method over the whole network graph is $O(N*L*\log N)$, where N is the number of nodes in the network, and L is the number of links in the network. For a connected graph with N nodes, L is lower-bounded by $N - 1$ in the case of a tree, and upper-bounded by $N*(N-1)/2$, in the case of a complete network.

Before straddling link algorithm starts to find rings, the network topology is read from an input '.snif' file and stored into a node to link adjacency matrix. Sample '.snif' files of USA and France Telecom networks can be found in Appendix II(a) and II(b) respectively.

The algorithm finishes execution within less than 1 second for all the sample networks listed below on a PIII-500 PC, which is equipped with 256MB RAM. Some statistics running straddling link algorithm over several sample long haul networks are listed in Table 3.1. The topologies of these networks can be found in Appendix I.

Table 3.1 Statistics Running Straddling Link Method

Note: for the figures listed as X/Y: X is obtained from node-disjoint path marking, while Y is obtained from link-disjoint path marking and non-simple ring removal.

Network Name	USA long haul	Japan long haul	France Telecom	MCI network	WorldCom network
Number of Nodes	28	56	44	41	27
Number of Links	44	85	69	60	41
Average Nodal Degree	3.14	3.04	3.14	2.93	3.04
Number of Rings Found	27/24	44/34	41/34	34/30	21/19
Mean Ring Length (number of hops)	6.70/6.25	8.95/7.62	6.83/6.29	9.12/9.20	6.43/7.11
Number of Uncovered Links	0/0	0/0	0/0	3/3	3/3

One can see that the straddling link heuristic yields a pretty good overall link coverage on the sample sparse mesh networks, which have average nodal degrees around 3. The number of rings found by link-disjoint path marking is a little fewer than that found by node-disjoint marking, because some non-simple rings are not adopted. However there is no obvious impact on the overall link coverage. In practice, we may specify an upper bound on the number of hops allowed in a ring.

We would also compare the performance of the straddling link algorithm with the K-shortest path ring-finding algorithm [41] written by TRLabs, University of Alberta. The TRLabs ring-finding algorithm is also based on merging disjoint path pairs, but with a much higher time and space complexity. The TRLabs algorithm basically works as the following: look at all the N*(N-1)/2 node pairs, where N is the number of nodes, even if the network is not complete; for each node pair, find out all the disjoint paths in between (let's say k paths in total), and then try to merge C_k^2 permutations of these paths as rings. Table 3.2 below compares the performance of our algorithm with the TRLabs algorithm. Execution time for both algorithms are obtained from the same PIII-500 PC equipped with 256 MB RAM. One can see that the straddling link algorithm has achieved a dramatic saving in time and space complexity, without obvious degradation on the overall link coverage.

Table 3.2 Comparisons Between The Straddling Link Method And The TRLabs Algorithm

Note: for the figures listed as X/Y, X is obtained from the straddling link method, while Y is obtained from the TRLabs algorithm.

Network Name	USA	Japan long haul	France Telecom	MCI	WorldCom
Number of Rings Found	24/219	34/642	34/615	30/359	19/104
Number of Uncovered Links	0/0	0/0	0/0	3/0	3/0
Execution Time (seconds)	0.02/0.3	0.03/1.6	0.03/0.95	0.03/0.81	0.01/0.23

3.3.1 Discussions

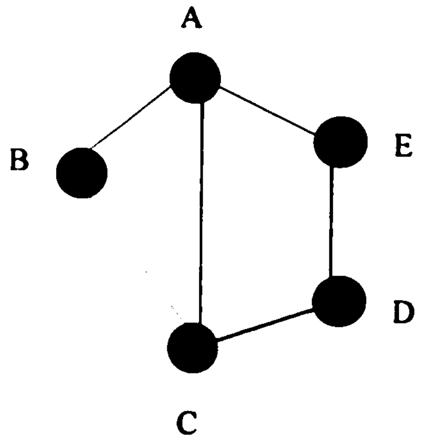


Fig. 3.11 **A Network Consisting of Two Elementary Rings**

An illustrative example is given in Fig. 3.11 above, to show why the straddling link algorithm can find a small ring set to cover most network links. In Fig. 3.11, by studying link A-C, the straddling link algorithm ends up with ring A-B-C-D-E-A, which covers all the network links. In terms of link coverage, ring A-B-C-D-E-A is equivalent to the combination of ring A-C-B-A and ring A-E-D-C-A, which are all elementary rings (rings that have no straddling links). In other words, the straddling link algorithm intends to find those rings that are formed by the merging of two elementary rings.

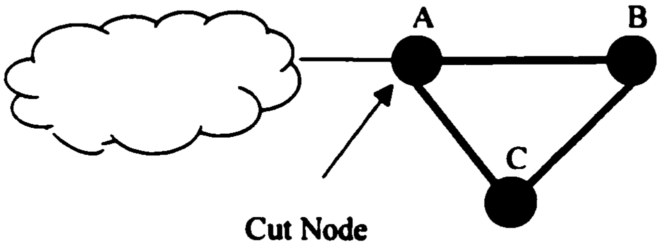


Fig. 3.12 A Special Topology

There are 3 uncovered links in MCI network and WorldCom network respectively. By studying the topologies of those two networks, we find that it is the same special topology that makes the straddling link algorithm unable to find covering rings for some links. Fig. 3.12 above depicts the special topology.

In Fig. 3.12, elementary ring A-B-C is connected to the rest of the network graph via node A, which is a cut node. Because link A-B, B-C and A-C are all of Case-2a, as specified in the straddling link algorithm, all those 3 links are skipped, and ring A-B-C will not be selected. However, ring A-B-C is the only ring that covers link A-B, B-C and A-C since node A is a cut node. So in general, the ring set from straddling link algorithm cannot cover those links along an elementary ring, which is connected to the rest of the network via a cut node.

Further analytical studies are needed to find out what are the other special topologies (if any) that make the straddling link algorithm unable to cover all the links. A simple 'patching' approach to fix up those uncovered links is: after the execution of the straddling link algorithm, if there is any uncovered link that is of Case-2a, merge the link itself with the second shortest path (if there is one) to form a covering ring.

3.4 Concluding Remarks

Summarizing our previous investigations, our straddling link ring finding algorithm has the following features:

1. Scalable: the number of rings will not exceed the number of links, while the resultant ring set covers most network links.
2. Based on node/link disjoint routing, thus can be easily implemented in a distributed manner, in wavelength routing networks.

We believe our straddling link method is a good engineering method for decomposing a network into link-covering rings, especially for sparse mesh networks with average nodal degrees around 3. The ring set obtained with such a method will be used in later studies on static WDM network protection and wavelength routing network protection respectively.

Chapter 4

A Generic Model for WDM Ring Cover Evaluations by Linear Programming

As we have discussed in previous chapters, a static WDM network is comprised of plain optical WDM switches, which do not have routing control modules and thus do not have knowledge about network topology and working/spare wavelength distribution over network links. Till now the best method we know to protect a static WDM network is WDM ring cover, which is very similar to the ring cover approach used to protection mesh SONET networks. A 'ring' in static WDM network protection refers to a logical self-healing ring, either of UPSR or BLSR logical type.

On the other hand, since P-cycle is proved to be a highly efficient topology for link protection, a natural question is whether we can use each ring as a P-cycle instead of as a pure ring, in the WDM ring cover approach, and whether we can improve the performance by making use of those ring-straddling links. We shall investigate this in this chapter by formulating the problem as an integer linear programming (ILP) setup.

4.1 Design Principles, Modeling Assumptions and Definitions

There are 2 general ways to make comparisons between two network protection/restoration methods [23]: (1) observe the difference in a certain performance figure when using the same amount of protection bandwidth; (2) observe the difference in the amount of protection bandwidth needed to achieve the same level of performance. We chose the former way to compare pure ring cover with P-cycle cover, and the performance figure we use here is network restorability which is defined as:

Restorability = $\sum_{i=1}^{L} P_i \;/\; \sum_{i=1}^{L} W_i$, where L is the total number of links in the network, P_i is number of protected working wavelengths on link i, and W_i is number of working wavelengths on link i. In another word, restorability is the percentage of total working wavelengths in the whole network that is restorable by WDM ring cover.

The outputs of a standard ring cover planning problem generally include the logical type and capacity allocation of each ring, the subset of demands to be routed over each ring, the locations of inter-ring transition. However, our purpose here is not to obtain a planning scheme for a real world network, but to make the relative comparison between pure ring cover and P-cycle cover, in terms of network restorability. So to observe the difference between the restorabilities achievable by pure ring cover and P-cycle cover, the basic ideas are:

- To design a model common to both pure ring cover and P-cycle cover, except that in case of P- cycle cover, ring paths are used for the protection/restoration of ring-straddling links.
- To apply to the model only a few basic constraints, and neglect those trivial factors in real network implementation, such as the need for wavelength conversion, the backup in inter-ring transition (also known as 'dual-feed' [16]). The point is that we want a generic model independent of any particular traffic distribution pattern and implementation details, so that we can make comparisons between different ring sets without losing of generality.

We assume that we are only using self-healing rings of UPSR logical type (see Appendix III) in our generic model, because an UPSR based ring cover can be much more easily formulated as a integer linear programming (ILP) problem than a BLSR based ring cover.

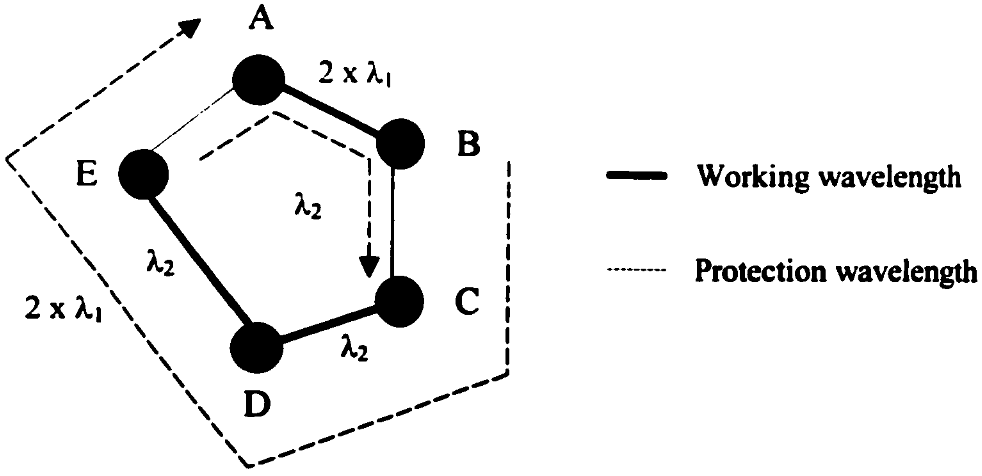


Fig. 4.1 **Capacity Allocation of A UPSR Ring**

We shall define the capacity allocation of a UPSR (Unidirectional Path-protection Switching Ring) as the sum of working demands protected by the UPSR ring. For example in Fig. 4.1 above, there is a demand of two wavelengths along A-B (protected by path B-C-D-E-A), and a demand of one wavelength along C-D-E (protected by path E-A-B-C). The total capacity allocation of UPSR ring A-B-C-D-E-A is thus 3 wavelengths. Generally, in a UPSR ring, a demand of one wavelength always occupies either a working or a protection wavelength on each link along the ring. So when we say the capacity allocation of a UPSR ring is X, it simply means that this ring occupies X wavelengths (maybe a mixture of working and protection wavelengths) on each link along the ring.

4.2 Integer Linear Programming Formulation of the Model

The objective function of our integer linear programming (ILP) model is to maximize network restorability, by means of WDM ring cover.

Assuming that K is the total number of candidate rings, and L is the total number of links in the network, the decision variables of the model include:

P_i, i = 1 … L, where P_i is number of protected working wavelengths on link i
C_j, j = 1 … K, where C_j is the capacity allocation of cycle j

The constants of the model include:
W_i, i = 1 … L, where W_i is number of working wavelengths on link i
U_j, j = 1 … K, where U_j is minimum number of spare wavelengths along cycle j
X_{ij} and X'_{ij}, i = 1 … L, j = 1 … K, where X_{ij} is an indicator for whether link i is on cycle j, and X'_{ij} is an indicator for whether link i is straddling cycle j
T_i, i = 1 … L, where T_i is the total wavelength capacity of link i (set arbitrarily to 12)

The complete ILP formulation is as the following:

Maximize: $\sum_{i=1}^{L} P_i$

Subject to:

$$0 \le P_i \le W_i \qquad \forall i \in L \qquad (1)$$

$$0 \le \sum_{j=1}^{K} X_{ij} \cdot C_j \le T_i \qquad \forall i \in L \qquad (2)$$

$$0 \le C_j \le U_j \qquad \forall j \in K \qquad (3)$$

$$0 \le P_i \le \sum_{j=1}^{K} X_{ij} \cdot C_j \qquad \forall i \in L \text{ (Used in case of pure ring cover)} \qquad (4a)$$

$$0 \le P_i \le \sum_{j=1}^{K} X_{ij} \cdot C_j + \sum_{j=1}^{K} X'_{ij} \cdot C_j \qquad \forall i \in L \text{ (Used in case of P-cycle cover)} \qquad (4b)$$

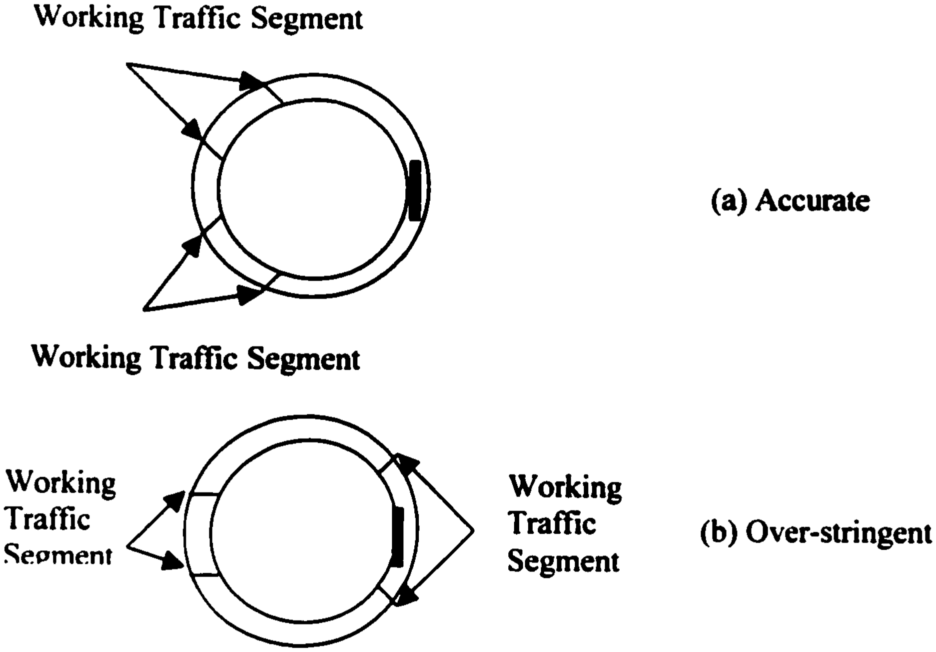
Note: each of the above constraints is actually a set of constraints.

4.2.1 Formulation Constraints

Constraint set #1 says that the number of protected working wavelengths on each link should not exceed the number of total working wavelengths on each link, which is a constant.

Constraint set #2 says that the aggregate capacity allocations of all the UPSR rings traversing a link should be less than or equal to the wavelength capacity of the link (refer to our modeling on network links in Section 2.2). This constraint is based on the notion that protection bandwidth cannot be shared between different rings in a static WDM ring cover network, which we have emphasized in Section 2.1.

Constraint set #3 says that capacity allocation of each ring is upper-bounded by the minimum number of spare wavelengths along the ring. This constraint is generally accurate, but a little bit over-stringent in some cases.



(a) Accurate

(b) Over-stringent

Fig. 4.2 **Constraint #3 -- Upper Bound on the Capacity Allocation of A UPSR Ring**

We depict in Fig. 4.2 above two different cases where the constraint set #3 can be accurate or over-stringent. We refer to 'working traffic segment' as either one or a series of links over which traffic goes from the source to the destination. The shaded bar on the ring represents the link that has the minimum number of spare wavelengths along the ring (U_j). In Fig. 4.2a, none of the working traffic segments traverses the link with the minimum number of spare wavelengths, and constraint set #3 is accurate, i.e., the capacity allocation of the ring is upper-bounded by U_j. In Fig. 4.2b, there is at least one segment of working traffic that traverses the link with the minimum number of spare wavelengths, and in this case, the capacity allocation of the ring may be higher than U_j.

There are some reasons why we choose constraint #3 as an approximate. We know that the working/spare wavelength distribution on network links is the result of the routing of end-to-end demand pairs. Therefore the capacity allocation of each ring is also determined by the routing of end-to-end demand pairs. Again our purpose here is not to obtain a real planning scheme for a particular traffic pattern across the network, but to make general comparisons between different ring sets, in terms of achievable restorability. So first in our simulative approach, the number of spare wavelengths on each link is randomly generated, and we use constraint set #3 as a simple but good estimation on the capacity allocation of each ring. Second, since we do not apply to our model those constraints in real world engineering, such as the need for wavelength conversion and the backup in inter-ring transition, we tend to obtain close to 100% restorability values. If the restorabilities of different ring sets are all very close to 100%, no performance comparison can be made between different ring sets. Constraint set #3 actually serves as a tightening factor to prevent the restorability from converging to 100%, and make the performance comparison between different ring sets possible.

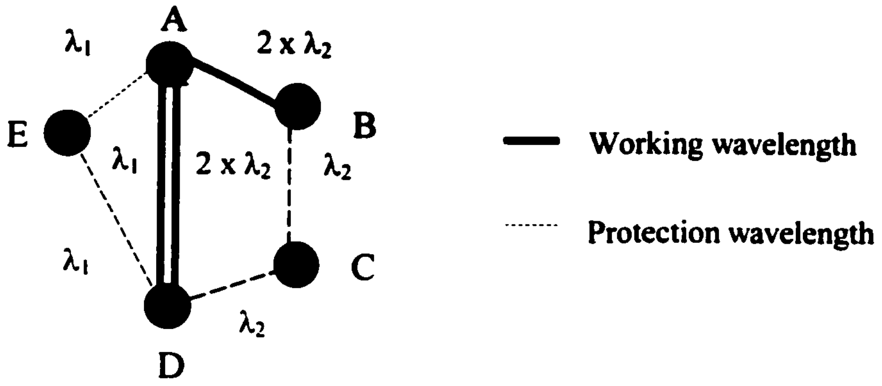
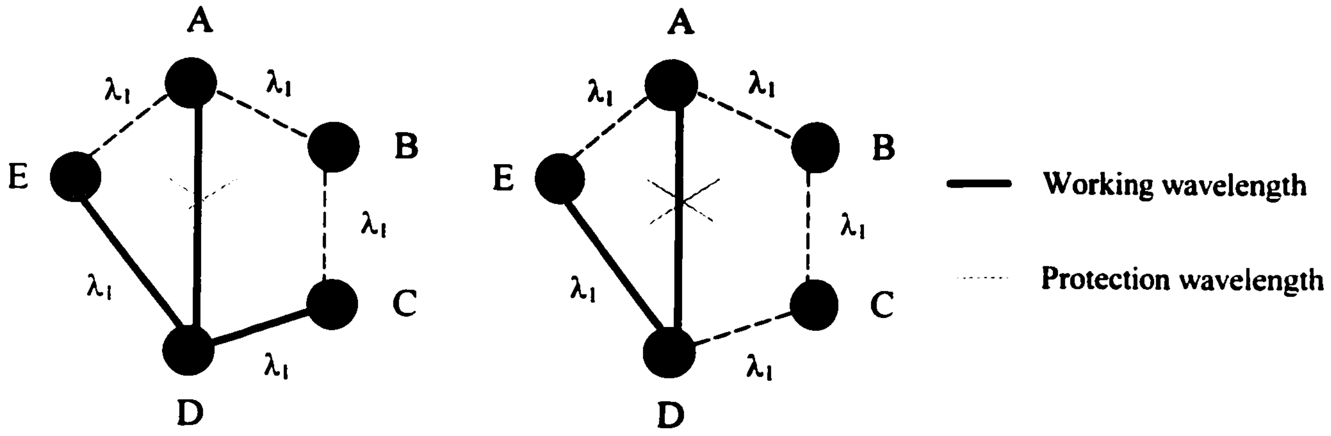


Fig. 4.3 Upper Bound on the Number of Protected Wavelengths on Each Link

-- Pure WDM Ring Cover

Constraint set #4a is applied to the case of a pure ring cover, while constraint set #4b is applied to the case of P-cycle cover. On top of constraint set #1, these two constraint sets also provide the upper bounds on the number of protected working wavelengths on each link. Constraint set #4a is saying that in a pure WDM ring cover network, the number of protected working wavelengths on each link is upper-bounded by the sum of capacity allocations of those rings, which have the link as an on-cycle link. An intuitive example on constraint set #4a is given in Fig. 4.3 above. In Fig. 4.3, the capacity allocation of UPSR ring A-D-E-A is 1 wavelength. The capacity allocation of UPSR ring A-B-C-D-A is also 1 wavelength, because the minimum number of spare wavelengths along ring A-B-C-D-A is 1. According to constraint #4a, the upper bound on the number of protected working wavelengths on link A-D should be: 1 + 1 = 2 wavelengths. Note that there are actually 3 working wavelengths altogether on link A-D, i.e., for this particular case, constraint #4a is tighter than constraint #1. There are also cases where constraint #4a is looser than or equivalent to constraint #1.



(a) (b)

Fig. 4.4 **Two Different Cases of Ring-straddling Link Restoration**

In the case of formulating a P-cycle cover, the contribution of ring paths to the restoration of ring-straddling links should also be taken into consideration. This is on top of the traditional self-healing ring based restoration, which is represented by the first term on the right hand side of the inequality in constraint set #4b. The second term on the right hand side of the inequality in constraint set #4b represents the upper bound on the contribution of ring paths to the restoration of a ring-straddling link. The term $\sum_{j=1}^{K} X'_{ij} \cdot C_j$ means that on each link, the number of working wavelengths protected as a ring-straddling link should not exceed the aggregate capacity allocations of those rings, which have the link as a ring-straddling link. In Fig. 4.4 (a) above, traffic segment C-D-E is protected by ring A-B-C-D-E-A, and if straddling link A-D fails, neither ring path A-B-C-D nor ring path A-E-D is feasible. In Fig. 4.4 (b), traffic segment D-E is protected by ring A-B-C-D-E-A, and if straddling link A-D fails, A-B-C-D is a feasible restoration path of capacity 1. In other words, if a link is straddling to a UPSR ring with capacity allocation X, it does not mean that there are 2 restoration paths available each of capacity X. Instead, a restoration path of capacity X is the best we can expect. From this respect, by using the term $\sum_{j=1}^{K} X'_{ij} \cdot C_j$ in constraint set #4b, we are optimistic about the amount of traffic on straddling links that is restorable with ring paths.

In summary, the generic model is to be used in the restorability comparison between pure WDM ring cover and P-cycle cover. Most of the constraints in the generic model are on a per link basis (with constraint set #3 as an exception), which is consistent with the fact that we are studying ring/cycle based link protection/restoration. Constraint set #1, #2 and #4a are all accurate bounding conditions, while constraint set #3 is a tight condition and constraint set #4b is a loose condition. It is hard to tell whether the effects of constraint set #3 and #4b will 'neutralize' with each other in case of P-cycle cover. What is more important is that constraint set #1, #2 and #3 are common to both pure WDM ring cover and P-cycle cover. Therefore we are interested in observing the performance difference caused by the second term on the right hand side of the inequality in constraint set #4b.

4.2.2 A Numerical Example

To give an illustrative example of our ILP model, consider the small network given in Fig. 4.5 below. The numbers of working and spare wavelengths on each link are listed in table 4.1.

Two rings are found in the network with the straddling link algorithm: ring A-B-C-E-A and ring B-C-D-E-B, whose capacity allocations are denoted as C_1 and C_2 respectively.

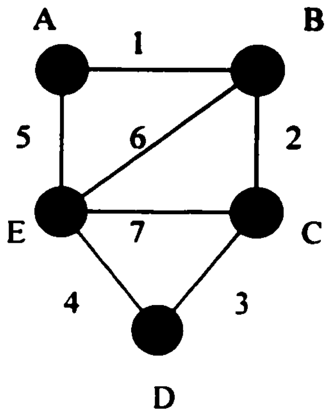


Fig. 4.5 An Illustrative Example

Table 4.1 Wavelength Distributions

Link ID	Number of Working Wavelengths	Number of Spare Wavelengths
1	$W_1 = 8$	$S_1 = 4$
2	$W_2 = 7$	$S_2 = 5$
3	$W_3 = 5$	$S_3 = 7$
4	$W_4 = 5$	$S_4 = 7$
5	$W_5 = 8$	$S_5 = 4$
6	$W_6 = 9$	$S_6 = 3$
7	$W_7 = 6$	$S_7 = 6$

Suppose we are trying to investigate the case of P-cycle cover, the generic model for the network shown in Fig. 4.5 looks like the following:

Maximize: $\sum_{i=1}^{7} P_i$

Subject to:

$0 \le P_1 \le 8$ (constraint set #1)
$0 \le P_2 \le 7$
$0 \le P_3 \le 5$
$0 \le P_4 \le 5$
$0 \le P_5 \le 8$
$0 \le P_6 \le 9$
$0 \le P_7 \le 6$

$0 \le C_1 \le 12$ (constraint set #2)
$0 \le C_1 + C_2 \le 12$
$0 \le C_2 \le 12$
$0 \le C_2 \le 12$
$0 \le C_1 \le 12$
$0 \le C_2 \le 12$
$0 \le C_1 \le 12$

$0 \le C_1 \le 4$ (constraint set #3)
$0 \le C_2 \le 3$

$0 \le P_1 \le C_1$ **(constraint set #4b)**
$0 \le P_2 \le C_1 + C_2$
$0 \le P_3 \le C_2$
$0 \le P_4 \le C_2$
$0 \le P_5 \le C_1$
$0 \le P_6 \le C_2 + C_1$
$0 \le P_7 \le C_1 + C_2$

4.3 Restorability Performance

4.3.1 Simulation Environments and Assumptions

We implemented and solved the above constrained maximization problem on WindowsNT platform, using C++ language and linear programming libraries provided by CPLEX 7.0. We choose 3 different candidate ring sets as the input:

Ring set #1, rings found by the straddling link algorithm and used as pure rings,

Ring set #2, rings found by the straddling link algorithm and used as P-cycles,

Ring set #3, rings found by TRLabs ring-finding algorithm and used as pure rings.

We generate a random number of spare wavelengths for each link using a normal distribution (μ,σ), where mean μ varies from 4.5 to 6.0 with a step length of 0.1. Using the modeling assumption on wavelength distribution in Section 2.2, we obtain a series of network-wise ratios of working/spare wavelengths that change roughly between 1.2 and 2.0. Variance σ takes either 1.5, or 2.0 or 2.5. Considering that the total capacity of each link is only 12, 2.5 is a pretty large variance.

To reduce effect of statistical fluctuation on network restorability, we carry out 100 simulations for the same (μ,σ) and then obtain the mean of network-wise working/spare ratio and the resultant restorability.

4.3.2 Simulation Results and Analyses

Some performance figures are given from Fig. 4.6 to Fig. 4.9 below. Here we only provide the results from USA long haul network and France Telecom network, because the basic trends are the same for other sample networks.

In all these 4 figures, the mean network restorability is a decreasing function in terms of the mean ratio of working/spare wavelengths. Fig. 4.6 and Fig. 4.7 further compare the performance of pure WDM ring cover under 3 different variances of spare wavelength distribution, in USA and France networks. From Figures 4.6-4.7, one can make the observation that under the same working/spare ratio, the higher the variance, the lower is the mean resotrability. In other words, the performance of the pure ring cover approach is sensitive to the distribution of wavelengths. Fig. 4.8 and Fig. 4.9 compare the performances of 3 different ring sets when the variance of spare wavelength distribution is fixed to 1.5, in USA and France networks. From Figures 4.8-4.9, one can make the observation that under the same working/spare ratio, there is very little performance difference between pure ring cover and P-cycle cover (ring set #1 and ring set #2); on the other hand, pure ring cover with the TRLabs ring set (ring set #3) peforms significantly better over pure ring cover with the SLA ring set (ring set #1).

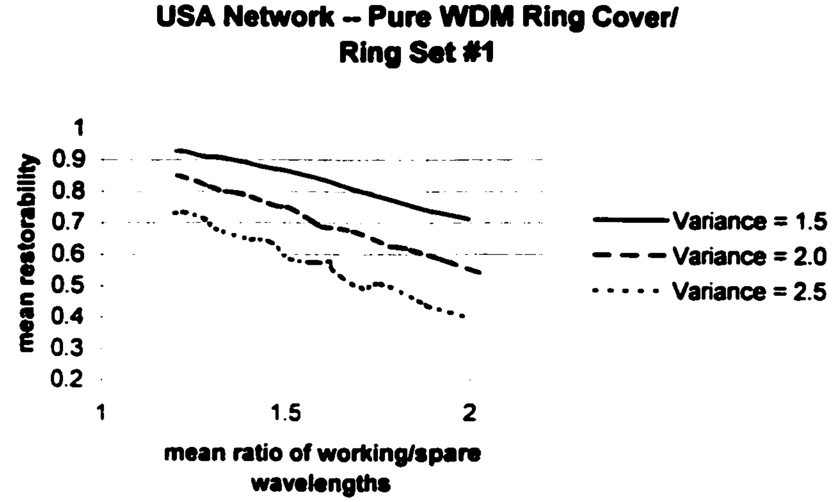


Fig. 4.6 USA Network – Pure WDM Ring Cover

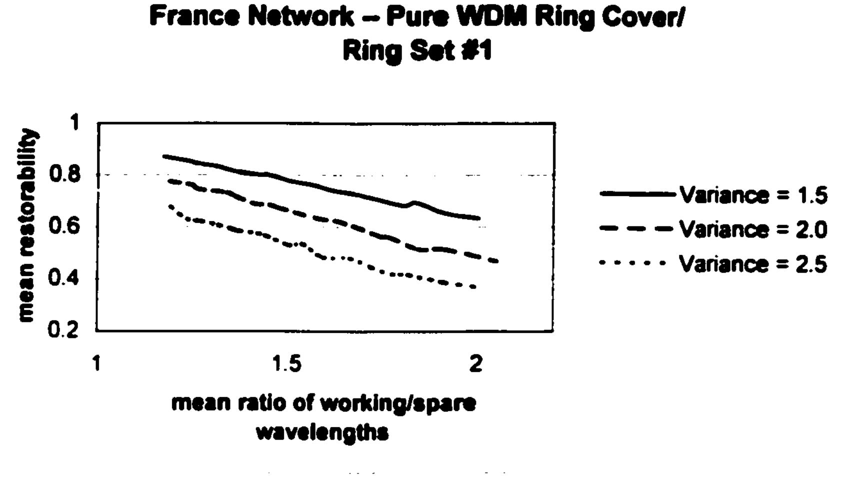


Fig. 4.7 France Network – Pure WDM Ring Cover

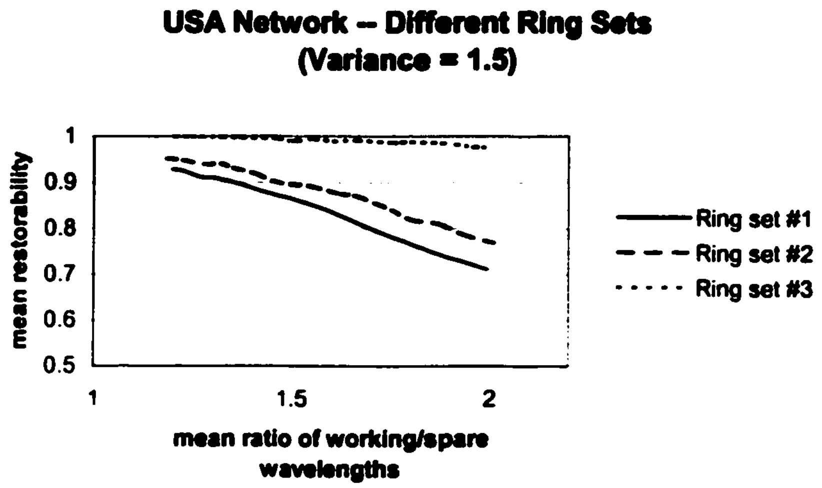


Fig. 4.8 USA Network – Different Ring Sets

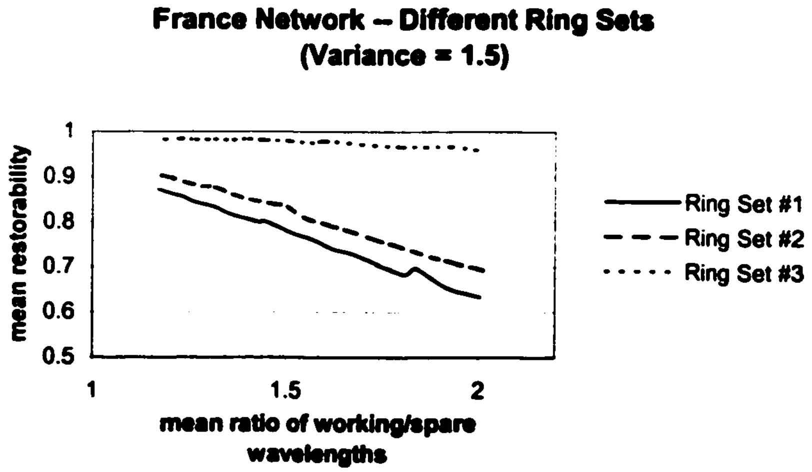


Fig. 4.9 France Network – Different Ring Sets

Here are some important observations and discussions based on the performance curves above:

1. From Fig. 4.6 and Fig. 4.7 we see that the performance of ring cover approach is sensitive to the variance of spare wavelength distribution, which is closely related to the routing scheme of

end-to-end demand pairs. More specifically, in the constraint set #3 of our integer linear programming model, the capacity allocation of each ring is upper-bounded by the minimum number of spare wavelengths along the ring, thus the higher the variance of spare wavelength distribution, the lower is the capacity allocation of each ring, and the lower is the restorability.

2. From Fig. 4.8 and Fig. 4.9 we see that there are some performance differences between P-cycle cover (ring set #2) and pure WDM ring cover (ring set #1), but the restorability improvement by using P-cycle cover is not dramatic (less than 10%). We know that the performance difference between P-cycle cover and pure ring cover is determined by the capacity allocations of those link-straddling rings, as it boils down from the second term on the right hand side of the inequality in constraint set #4b. Furthermore, the capacity allocation of each ring is bounded by constraint set #2. In other words, different rings compete with each other over protection bandwidth, and each ring ends up with a limited capacity allocation. All in all, the reason for the limited performance improvement is that protection bandwidth cannot be shared between different rings, in WDM ring cover networks.
3. We also see from Fig. 4.8 and Fig. 4.9 that there are quite some performance differences between ring set #1 (rings found by straddling link algorithm, pure ring cover) and ring set #3 (rings found by TRLabs algorithm, pure ring cover). It looks that using more rings does help improve network restorability. On the other hand, more rings introduces more complexities in real network operation and maintenance. Take USA network for example, there are 24 rings in ring set #1, while there are 219 rings in ring set #2. Will we setup and maintain about 10 times the number of logical self-healing rings in that case, just to obtain the restorability improvement? The answer is no of course. The complexity (number of rings to use) and performance (achievable restorability) is a pair of tradeoff, and the ring set found by the straddling link algorithm reduces the complexity dramatically yet provides acceptable performances.

In order to have an idea on how close the above statistical restorability is to the 'real' restorability, we also obtained the 95% confidence intervals [45,46] of our sample data. Fig. 4.10 below shows the sample 95% confidence intervals from the USA network, when using ring set #2. We see that the intervals are quite small compared with the means. Although not shown, we have similar observations for other experimental data. Therefore, we believe that a sample size of 100 simulations is large enough for us to estimate the restorability.

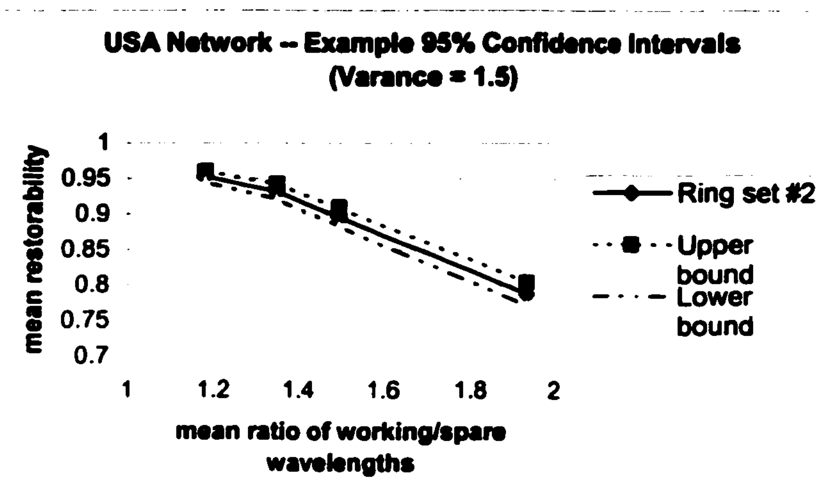


Fig. 4.10 Example 95% Confidence Intervals

4.4 Concluding Remarks

Based on the above simulative studies with our generic integer linear programming model, we come to the conclusion that in WDM ring cover networks, it is not worthwhile to modify a mature self-healing ring protocol (like UPSR or BLSR) such that those ring-straddling links can be protected by ring paths. There are mainly two reasons:

1. We have already observed that the performance improvement of P-cycle cover over pure WDM ring cover is not dramatic, because protection bandwidth cannot be shared between different rings, in a static ring cover network. Actually we have been optimistic even for that little performance improvement, because constraint set #4b is a loose bounding condition as emphasized before.
2. From the engineering point of view, it is not practical to update a mature self-healing ring protocol to P-cycle protection. In a sense the whole idea of self-healing ring is a 'hard-provisioned' means of protection/restoration at the second layer. Based on the simple and symmetric ring topology, the restoration signaling is simple and fast. The attempt to introduce straddling link protection/restoration will break the symmetry of ring topology, and make the restoration signaling much more complicated.

Therefore, pure ring cover is still the best-known approach to protect static WDM networks. In addition to the fact that ring cover is a hard mathematical problem to solve, which we have discussed in Section 1.4.2.2, There are a few disadvantages with the ring cover approach in engineering practice:

(I) Low bandwidth efficiency

Within each ring, there is 100% bandwidth redundency, and network-wise bandwidth redundency may be even higher.

(II) Sensitive to end-to-end routing scheme and the accuracy of demand prediction

The change of working/spare bandwidth distribution on a link may lead to the change of the capacity allocations of all the rings traversing that link. Thus the achievable restorability of a WDM ring cover network is sensitive to both end-to-end routing scheme and the accuracy of demand prediction.

(III) Hard to scale

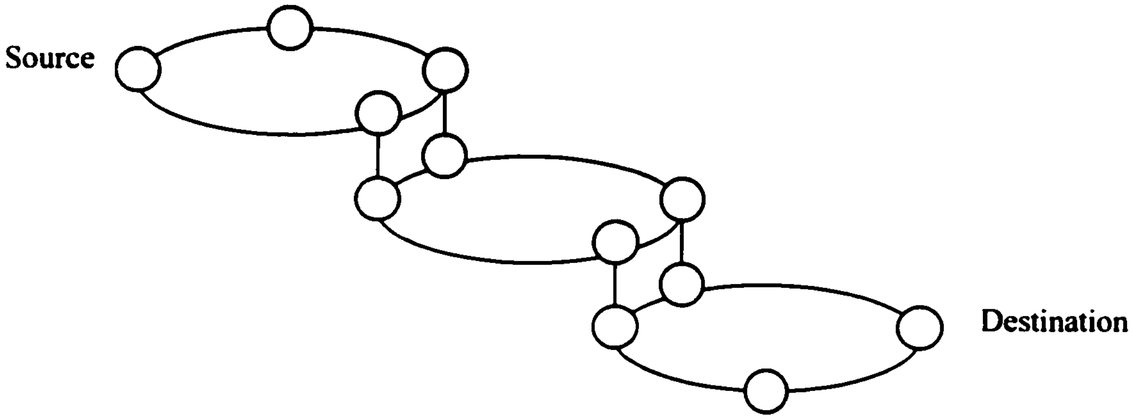


Fig. 4.11 An End-to-end Lightpath Traverses Multiple Rings

Ring cover networks are very hard to scale. Firstly, all the end-to-end lightpaths and self-healing rings have to be setup by a network operator manually. Secondly, very often an end-to-end lightpath traverses multiple rings, as shown in Fig. 4.11 above. The desired bandwidth has to be available all the way around each of those rings. If bottleneck occurs at one of the rings, all the OXCs and OADMs along that ring have to be upgraded. There are cases where it took several months to setup a coast-to-coast path in a ring cover network [5,8].

However, it is unfair to say that all those disadvantages are ring cover's fault. In fact, those problems are inherent to static WDM networks or SONET networks, which are comprised of nodal equipments with no layer 3 intelligence. With the recent developments in wavelength routing (refer to Section 1.1), it would be interesting to see how we should use ring/cycle topologies in the protection/restoration of more intelligent optical transport networks.

Chapter 5

Distributed Ring-based Protection/Restoration in Wavelength Routing Networks

From our discussions in previous chapters, we realize that in order for a DWDM network protection/restoration approach to be flexible and scalable, it has to be distributed. Distributed network protection/restoration refers to autonomous and collaborative actions taken by the routing equipments to survive a node/link failure. The restoration paths are neither calculated offline, nor hard provisioned.

Distributed network protection/restoration requires that each node has in its local database (i) either part of or all of the network topology, and (ii) bandwidth distribution over links in the network, i.e., third layer intelligence. An easy confusion is that distributed protection/restoration has to be done at the network layer, for example at IP layer. With the recent developments in DWDM networking, wavelength routing networks are coming into reality. In a wavelength routing network, each wavelength router stores in its local database a network-wise topology and the working/spare wavelength distribution across network links; the database content is synchronized by a distributed OSPF-like wavelength routing protocol [5,6,8,10]. In the wavelength routing protocol, in addition to the link-state flooding upon a network topology change, changes in the number of working/spare wavelengths on each link are also synchronized across the network in a similar way. We are looking for a distributed protection/restoration method to work as an indispensable part of the WDM layer, based on the wavelength routing protocol.

5.1 Basic Ideas

Traditionally, people use tree topologies more than rings/cycles in distributed network protocols. First, there are a handful of simple algorithms available to find one or a set of spanning trees to cover the whole network graph [21,42], whereas as we have discussed in Chapter 1 and Chapter 3, it is hard to guarantee 100% node/link coverage with a scalable set of rings/cycles. Second, tree algorithms by nature are easy to be implemented in a distributed routing network, e.g., by multicasting, whereas cycles are usually to be avoided in most routing protocols.

Distributed Cycle Pre-Configuration (DCPC) [22,23] is one of those few distributed ring-based protection/restoration protocols ever proposed. In the protocol a special in-band signaling called 'statelet' has been defined, and the statelets serve as the mesh equivalent of K1/K2 bytes in BLSR SONET rings [16,17]. The protocol involves a series of forwarding and flooding of statelets before a failure occurs, in order to obtain a set of P-cycles from the highest score (refer to Section 1.4.2.3) to the lowest score across the network. From an engineering point of view, DCPC protocol is not easy to be implemented, and also it is not quite necessary to carry on those complicated statelet forwarding and flooding procedures just to obtain those P-cycles with the highest scores.

Still there are two valuable ideas from the DCPC protocol. The first idea is distributed pre-failure planning, which means that restoration paths are 'prepared' at each node in anticipation of the failure of an adjacent link, so as to speed up the restoration process. Discussions on distributed pre-failure planning can also be found in [26]. The second idea is that when we have found a ring in a distributed routing network, we should try to use it as a P-cycle instead of a pure ring. As introduced earlier, the bandwidth efficiency of the P-cycle topologies is much higher than that of pure rings.

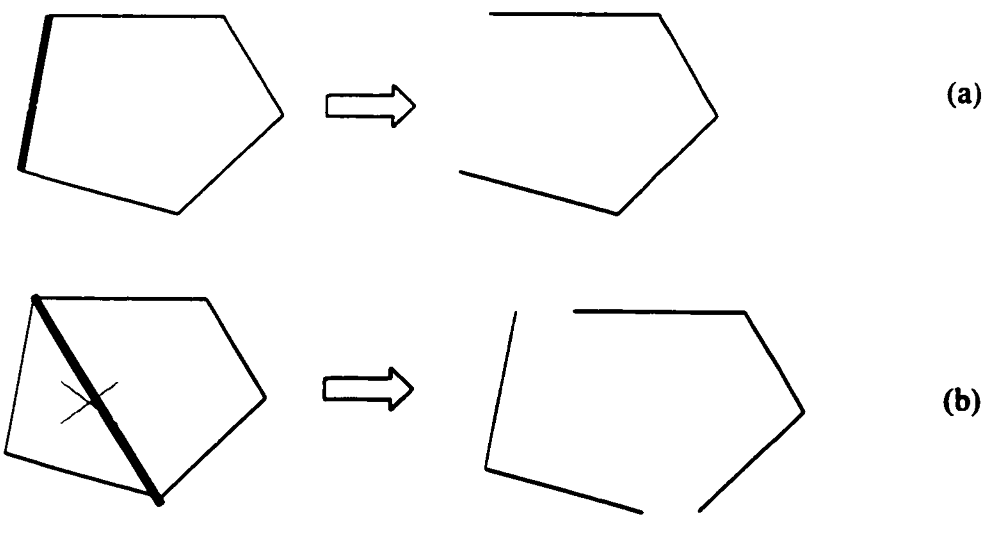


Fig. 5.1 **Ring/P-cycle Topologies in Wavelength Routing Network Protection**

The distributed ring-based approach we propose here is based on such a notion: in network protection/restoration, whether we are talking about pure rings or P-cycles, it is all about restoration path(s). For a wavelength routing network, both rings and P-cycles can be viewed as topological patterns to provide independent link restoration paths for each node covered. That is different from the situation in static WDM networks where a self-healing ring has to work as a whole. In Fig. 5.1 above, we show how ring/P-cycle topologies can be used in the protection/restoration of wavelength routing networks.

In Fig. 5.1 (a), if one of the links on the ring fails, the node adjacent to it knows that topologically there is a rerouting path the other way around the ring. Similarly as shown in Fig 5.1 (b), the node knows that if a ring-straddling link fails, topologically there are two node-disjoint rerouting paths both ways around the ring. To find link-covering rings in a wavelength routing network, remember each wavelength router has a local database regarding network-wise topology and bandwidth distribution. A node can find those rings cover it from the local topology database, and then share such knowledge with all other nodes along the rings.

Since ring-based rerouting is the essential idea of the distributed protection/restoration we propose here, we name it Distributed Ring-based Rerouting (DRR) protocol.

5.2 Implementation Details

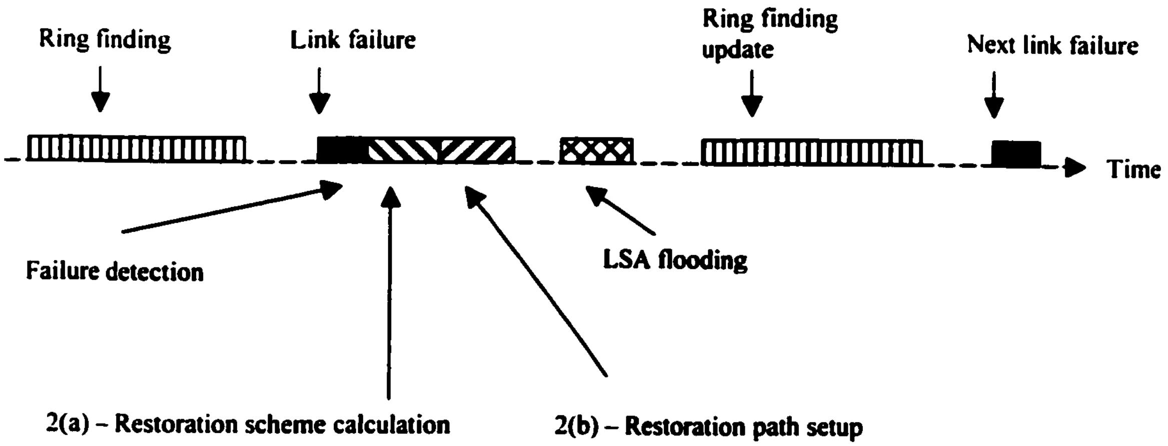


Fig. 5.2 Timing Diagram of the DRR Protocol

When a link fails, the whole DRR protocol is executed in two stages: ring finding and link restoration, as shown by the timing diagram in Fig. 5.2 above.

Ring finding in Stage-1 is based on the distributed version of the straddling link algorithm we presented in Chapter 3. We propose to base distributed ring finding algorithm on the wavelength routing protocol, in order to collect information on link restoration paths before a link failure occurs.

Link restoration in Stage-2 is carried out after the link failure has been detected, by using the restoration paths obtained from the decomposition of those rings that cover the failed link. There are two sub-stages in Stage-2:

(a) Restoration scheme calculation

In this sub-stage, calculations are made to determine the wavelength capacity of each pre-planned restoration path, so as to reroute as much disrupted traffic as possible. That is what we call the maximum rerouting flow (MRF) problem, which will be discussed in full details in Section 5.2.2.

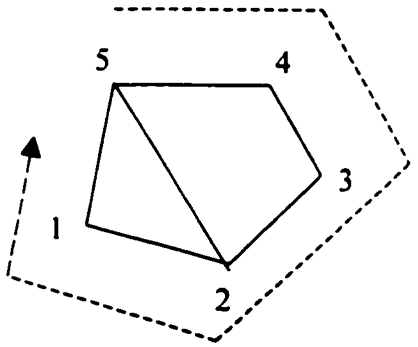
(b) Restoration path setup

Based on the results of sub-stage 2(a), restoration lightpaths are physically setup in this sub-stage, with a wavelength distribution protocol (refer to Section 2.2 on wavelength routing and distribution protocols).

5.2.1 Ring Finding Stage

The ring finding stage can be understood from both static and dynamic point of views. We discuss on the static operations of our distributed ring finding algorithm in Section 5.2.1.1, and then in Section 5.2.1.2 we discuss on the dynamic behaviors of such a distributed approach in real world networks.

5.2.1.1 Distributed Straddling Link Algorithm



Owner = 5	Ring = 5, 4, 3, 2, 1	Flag = 'ADD'

Fig. 5.3 **Distributed Execution of the Straddling Link Algorithm**

We mention at the end of Chapter 3 that the straddling link ring-finding algorithm can be easily implemented in distributed routing networks such as a wavelength routing network. Our Straddling Link Algorithm treats ring finding as a special routing problem, and has much less time complexity than classical ring enumeration algorithms. The distributed execution of the straddling link algorithm is illustrated in Fig. 5.3 above. We assume that the protection/restoration of each link is the responsibility of the 'owner node', which is an end-node with a larger node ID. The end-node of a link with a smaller node ID is referred to as the link's 'backup owner node'. For example in Fig. 5.3, node 5 is the owner node of link 5-1, 5-2 and 5-4, and node 4 is the owner node of link 4-3.

In Fig. 5.3, node 5 knows from its local network topology database that the nodal degrees of both itself and node 2 (one of its adjacent nodes) are greater then or equal to 3. By running Dijkstra's algorithm iteratively between node 5 and node 2, node 5 knows further that the second shortest path between node 5 and node 2 is path 5-1-2, and the third shortest path between node 5 and node 2 is path 5-4-3-2. Thus link 5-2 is of type 1a (refer to Chapter 3). Those two paths form the ring 5-4-3-2-1-5, with link 5-2 being a straddling link. Now ring 5-4-3-2-1-5 has Node 5 as its owner node, and node 2 as its backup owner node. Each ring has only one owner node and one backup owner node. Node 5 periodically propagates along ring 5-4-3-2-1-5 a signaling packet as formatted in Fig. 5.3, so as to share the knowledge about such a ring topology with all the other nodes along the ring. Consequently, the rerouting tables at all the nodes along the ring are updated, as shown in Fig. 5.4 below. Note that in the rerouting table at node 5 there are 2 rerouting paths for link 5-2, because it is straddling to ring 5-4-3-2-1-5.

Rerouting table at node 5:

Link	Rerouting path
5-1	5-4-3-2-1
5-4	5-1-2-3-4
5-2	5-1-2
5-2	5-4-3-2

Rerouting table at node 4:

Link	Rerouting path
4-3	4-5-1-2-3

Rerouting table at node 3:

Link	Rerouting path
3-2	3-4-5-1-2

Rerouting table at node 2:

Link	Rerouting path
2-1	2-3-4-5-1

Fig. 5.4 Updated Rerouting Tables (link restoration)

The same procedures above are repeated for each ring found by the Straddling Link Algorithm, whether the link is of type 1a or type 1b. Each ring provides one rerouting path for each on-cycle link, and a pair of node-disjoint rerouting paths for each straddling link. Finally each link covered by the straddling link ring set has at least one link restoration path, which is obtained from ring decomposition and stored in the rerouting table of the owner node. The same rerouting path may be found more than once for a link, and in that case only one distinct rerouting path is kept in the rerouting table. For example, in Fig. 5.5 below, link B-E is a straddling link for both ring A-B-C-D-E-A and ring F-B-C-D-E-F; thus only one instance of path B-C-D-E is used for link B-E.

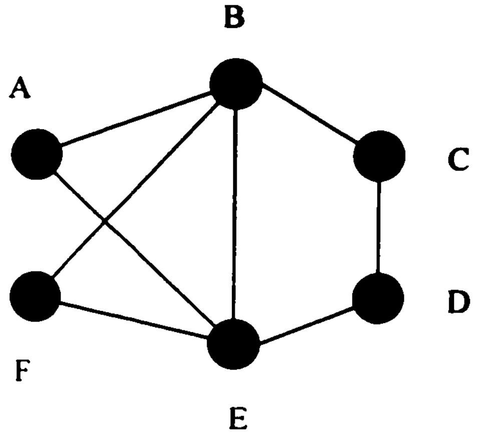


Fig. 5.5 **An Example of Duplicated Rerouting Path**

The significance of pre-failure planning of rerouting paths in the DRR protocol can be understood from two aspects. First, restoration is more or less speeded up, because the owner node of a failed link does not have to find out a lot of restoration paths from scratch. Second, link restoration is done in an organized and predictable way. Because in a given network graph, the DRR rerouting path set for each link is deterministic. That makes it much easier for a network operator to keep track of and analyze the link restoration activities in the network.

We give in Table 5.1 below the results from USA Long Haul and France Telecom networks. From Table 5.1 we find that for a given link, usually it is hard to guarantee that the rerouting paths found by the first stage of the DRR protocol are link-disjoint with each other. This is because the average nodal degrees of both networks are around 3, which are less than the mean numbers of rerouting paths per link. Although one can set the maximum allowable length of a rerouting path to a larger number, our results in Table 5.1 show that few rerouting paths exceed 8 hops in both networks (remember that the straddling link algorithm is liable to find shorter rings). Thus for practical considerations such as restoration speed, we set the maximum allowable length of a rerouting path to 8 in our subsequent discussions.

Table 5.1 Statistics of the Rerouting Paths Found: USA and France Networks

Note: for figures listed as X/Y, X is obtained under the condition that maximum allowable length of a rerouting path equals to 8, while Y is obtained under the condition that maximum allowable length of a rerouting path equals to 10.

	Mean Number of Rerouting Paths Per Link	**Mean Length of Rerouting Paths**
USA Long Haul	4.614/4.614	4.823/4.823
France Telecom	3.729/3.886	4.705/4.917

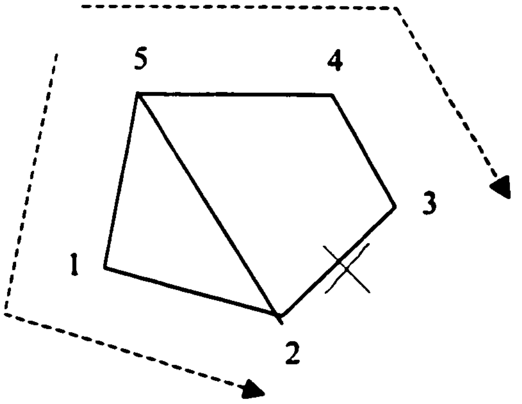
5.2.1.2 Ring Finding Update

From a dynamic point of view, the ring finding stage of the DRR protocol is an ongoing process and is triggered by the changes in network topology. When the network topology changes, there is a flooding of link-state advertisements (LSA) across the network to update the local topology databases at each node. That is part of the functionalities of the wavelength routing protocol. Right after that, those affected rerouting tables should also be updated accordingly. Specifically there are 4 types of possible topology changes: addition of a new link, addition of a new node, failure of a link, and failure of a node. Depending on the type of the topology change, there are different strategies to update the affected rerouting tables.

If a new link is added between two nodes, the owner node of the link checks in its local database if both nodal degrees are now greater than or equal to 3. If so, the owner node checks further if the new link is of type 1a or 1b. When a new ring is feasible as specified by the straddling link algorithm, the owner node of the new link as well as the new ring will start propagating the ring topology along the ring itself.

If a new node is added to the network, there must be at least 1 new link added simultaneously to connect the new node to the old network graph. If any of the new links is of type 1a or 1b, the owner node of the new link will start a ring topology propagation process, just like in the previous case where a single link is added.

If a link fails, upon receiving a link state advertisement (LSA) message about such a topology change, each ring owner node in the network checks if the failed link is on or straddling to one of the rings that the owner node is in charge of. If the failed link is an on-cycle link, for example link 3-2 in Fig. 5.6 below, node 5 will propagate a signaling packet (see Fig. 5.6) both ways along ring 5-4-3-2-1-5, notifying the other nodes along the ring that all the rerouting paths based on this ring should be removed. If the failed link is a straddling link, for example link 5-2 in Fig. 5.6, node 5 will simply remove link 5-2 from its list of adjacent links.



Owner = 5	Ring = 5, 4, 3, 2, 1	Flag = 'REMOVAL'

Fig. 5.6 Rerouting Path Removal in Case of Link 3-2 Failure

If a node goes down, its effect is equivalent to the simultaneous failures of all the links connecting the node to the rest of the network graph. Each of those link failures is dealt with one by one in the way as a single link failure. If the failed node is the owner node of a ring, the backup owner node of the ring will initiate the propagating process to update related rerouting tables.

We know that the synchronization of local topology databases is done network-wise via flooding of LSA messages. In contrast, for all 4 types of topology changes, the rerouting table update happens only at affected nodes, i.e., those nodes on the rings that cover the failed link. In this way we keep the impact of a link failure comparatively localized, and that is the pivotal ideal of link protection/restoration.

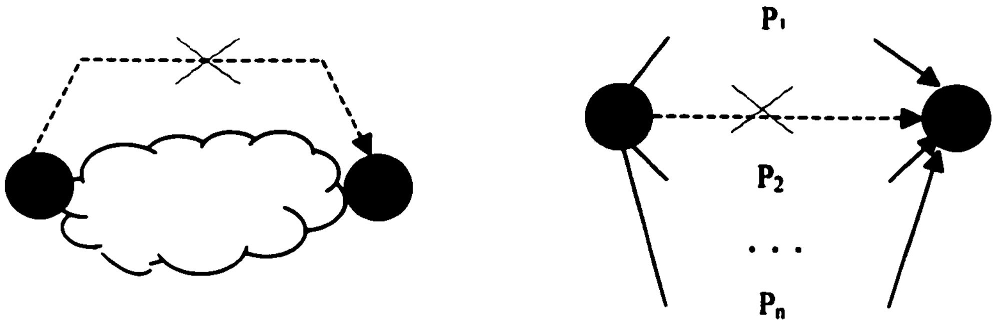
It is important for each node to decide what to do with its rerouting tables, upon receiving a link-state advertisement (LSA) saying that the working/spare wavelength distribution over its rerouting paths has changed. In that case, we propose that nothing should be done with the rerouting tables. Here we apply once more the commonly used methodology that the topology factor be decoupled from the traffic distribution factor. As long as a rerouting path is topologically feasible, even if there is no spare wavelength along the path at a given time, we will still keep the rerouting path for possible use in later link restoration. We know that in a wavelength routing network, the working/spare wavelength distribution over links changes at a regular basis. It does not make sense to favor rerouting path A over rerouting path B, just because path A has a larger spare capacity than path B at a time before the link failure. In the DRR protocol, the bandwidth distribution factor will not be considered until a link failure occurs.

5.2.2 Link Restoration Stage

The ring finding stage of the DRR protocol is a distributed pre-failure planning, or preparation. When a link failure does occur, we come to the second stage of the DRR protocol, where link restoration is carried out.

5.2.2.1 The Maximum Rerouting Flow (MRF) Problem

A decision needs to be made in sub-stage 2(a) to reroute the disrupted traffic over the rerouting path set found by ring decomposition. Generally speaking, sub-stage 2(a) is aimed at solving a maximum rerouting flow problem (MRF), i.e., to reroute the disrupted traffic as much as possible, by choosing the wavelength capacity of each restoration path properly. Sub-stage 2(b) is just a process to setup rerouting paths with the wavelength distribution protocol, after the wavelength capacity of each path has been determined in sub-stage 2(a).



(a) Based on the whole network (b) Based on the DRR path set

Fig. 5.7 Maximum Rerouting Flow Problem

If there is no pre-failure planning or preparation, the owner node of the failed link has to consider the whole network graph for the maximum rerouting flow problem, as shown in Fig. 5.7 (a) above. The maximum rerouting flow based on the whole network graph is a theoretical upper bound, which cannot be exceeded by any link restoration methods. On the other hand, it is obvious that the space of possible rerouting paths is very large.

In contrast, the DRR protocol considers only a small set of rerouting paths that have already been chosen before a link failure, as depicted in Fig. 5.7 (b), We will see in Section 5.3 that although the pre-selected rerouting path set is small (e.g. in Table 5.1), the restoration performance of the DRR protocol can be very close to the maximum rerouting flow based on the whole network graph, which is the theoretical upper bound.

5.2.2.2 ILP Formulations and Algorithms for the MRF Problem

We give below the integer linear programming (ILP) formulations of the maximum rerouting flow problem, based on both the whole network graph and the DRR path set. Note that in our model of network links (refer to Section 2.2), there are N pairs of bi-directional wavelengths within each link A-B. If a traffic demand of one λ traverses link A-B, it will always occupy a pair of bi-directional wavelengths on link A-B. Under such a link modeling assumption, classical maximum flow algorithms such as labeling algorithm [43] and flow augmenting path algorithm [40] do not work, because they assume directional links. We set up integer linear programming models for the maximum rerouting flow problem, since the MRF problem turns out to be nothing but a constrained linear optimization problem, which has a linear objective function and linear constraints.

The objective functions in both ILP formulations are still network restorability, the performance figure we have used in Chapter 4 to evaluate various WDM ring cover approaches. Restorability is still defined as the percentage of total working wavelengths in the whole network that is restorable. However, in the context of wavelength routing networks where protection bandwidth can be shared at the WDM layer, it should be understood in a different way. In a static WDM network, different rings compete with each other over spare bandwidth. Thus it is a network-wise optimization problem to decide the capacity allocation of each ring so as to maximize total restorability of a network. While in a wavelength routing network, under the assumption that only one link failure may occur at a given time, the rerouting for one link failure is independent of the other. As a result, the MRF optimization problem involved in sub-stage 2(b) is totally up to the owner node of the failed link, which regards all the spare wavelengths in the network as available for its own rerouting purposes. So in a wavelength routing network, the network-wise restorability is the mean of the restorability of each link.

a) ILP formulation for the maximum rerouting flow based on the whole network graph

Without loss of generality, we assume that i is the link ID of the failed link, source node s is the end node of link i with a smaller node ID, and destination node d (also referred to as the sink node) is the end node of link i with a larger node ID. Our objective function is to maximize the total flow out of the source node and into the destination node, by considering the whole network graph.

The decision variables of the ILP model include:

$Flow\_X_t$: directional flow over link t that goes from the node with smaller ID to the node with larger ID

$Flow\_Y_t$: directional flow over link t that goes from the node with larger ID to the node with smaller ID

The constants of the ILP model include:

E_{ij}: indicator for whether node i is the end node of link j with a smaller node ID

(E_{ij} is a constant because it is fixed when a graph is given)

W_i: number of working wavelengths on link i

S_i: number of spare wavelengths on link i

The complete ILP formulation is as the following:

Maximize: $$\sum_{\text{each link t adjacent to source node}} (Flow\_X_t - Flow\_Y_t)\, E_{st}$$

(i.e., total flow out of the source node)

Subject to: $Flow\_X_i = 0,\ Flow\_Y_i = 0$ (1)

(i.e., no flow over the failed link)

$Flow\_X_j + Flow\_Y_j \le S_j,\ \forall j \in L$ and $j \neq i$ (2)

(i.e., capacity constraint on each link)

$$\sum_{\text{each link t adjacent to source node}} (\text{Flow\_X}_t - \text{Flow\_Y}_t)\ E_{st} \le W_i \qquad (3)$$

(i.e., total amount of rerouting flow should be no more than the disrupted traffic)

$$\sum_{\text{each link t adjacent to sink node}} (\text{Flow\_Y}_t - \text{Flow\_X}_t)\, E_{dt} = \sum_{\text{each link t adjacent to source node}} (\text{Flow\_X}_t - \text{Flow\_Y}_t)\, E_{st} \qquad (4)$$

(i.e., flow into the sink node equals flow out of the source node)

$$\sum_{\text{each link t adjacent to node j}} (\text{Flow\_X}_t - \text{Flow\_Y}_t)\, E_{jt} = 0,\ \forall j \in N \text{ and } j \ne s, j \ne d \qquad (5)$$

(i.e., flow conservation at all intermediate nodes)

There is a noteworthy point regarding the ILP formulation for MRF based on the whole network graph. We apply constraint (4) and (5) according to classical maximum flow theory, i.e., flows are defined at a per link basis. However, in the context of rerouting with lightpaths in a wavelength routing network, each lightpath consumes the same number of wavelengths on each link it traverses, this is referred to as the consistency condition. So MRF based on the whole network graph is the theoretical upper bound, not only in the sense that it considers all the possible restoration paths, but it also neglects the consistency condition in WDM lightpath setup.

b) ILP formulation for the maximum rerouting flow based on the DRR path set

Without loss of generality, we assume that i is the link ID of the failed link. Our objective function is to maximize the total flow over the DRR path set previously found.

The decision variables of the ILP model include:

PATH_FLOW_{ij}: partial rerouting flow that goes over rerouting path j for the failure of link i

The constants of the ILP model include:

W_i: number of working wavelengths on link i

S_i: number of spare wavelengths on link i

Q_{ij}: indicator for whether link i is on rerouting path j

The complete ILP formulation is as the following:

Maximize: $$\sum_{j=1}^{Mi} \text{PATH\_FLOW}_{ij}$$

Subject to:

$$\sum_{j=1}^{Mi}(\mathrm{PATH\_FLOW}_{ij})Qtj \le S_t,\ \forall t \in L \text{ and } t \neq i \qquad (1)$$

(i.e., the sum of the rerouting flows over each link should be less than the spare capacity on the link)

$$\sum_{j=1}^{Mi}\mathrm{PATH\_FLOW}_{ij} \le W_i \qquad (2)$$

(i.e., total amount of rerouting flow should be no more than the disrupted traffic)

c) Greedy heuristic for maximum rerouting flow based on the DRR path set

It may not be realistic to assume that each node is equipped with a ILP solver, thus we also propose a greedy heuristic, for maximum rerouting flow based on the DRR path set. The implementation of the greedy heuristic is very simple, yet we will see that it can perform quite close to the ILP-based solution.

For the failure of link i, the procedures of the greedy heuristic are given in pseudo-code form, in Fig. 5.8 below. Rerouting paths are sorted in ascending sequence of path length. As we can see from the pseudo-codes, the heuristic tries to push as much rerouting flow as possible over each path, starting from the shortest one. That is why we say it is ‘greedy’.

```
Greedy heuristic algorithm
begin
        j := 1;
        do
                /* Obtain the minimum spare capacity along path j */
                tmp := min_spare( j );
                /* Determine the partial rerouting flow over path j */
                PATH_FLOW_ij := tmp;
                /* Update available spare capacity along path j */
                for each link k along rerouting path j do
                        k.spare := k.spare – tmp ;
                end;
                j ++ ;
        while j ≤ M_i
end;
```

Fig. 5.8 **Pseudo-codes of the Greedy Heuristic**

5.3 Performance Evaluations

The 3 algorithms for the MRF problem are implemented on a PIII-500 PC equipped with 256MB RAM. The typical execution time for all 3 algorithms is around several tens of milliseconds. The integer linear programming part involved in the first two algorithms is implemented with the C++ libraries of CPLEX 7.0, whereas the greedy heuristic is simply coded with plain C.

There are two comparisons we want to make here:

1. We are interested in observing the rerouting performance of DRR path set/ILP relative to MRF based on the whole network graph, which is the theoretical upper bound. That will give us an idea whether we can achieve satisfactory link restoration with the DRR path set.
2. We also want to know the rerouting performance differences between DRR path set/greedy heuristic, and DRR path set/ILP, which is the best we can do with those rerouting paths obtained from ring decomposition. That will give us an idea whether the greedy heuristic is acceptable from an engineering point of view.

Whenever DRR path set is involved, we set 8 as the maximum allowable hop count of a rerouting path, due to some practical concerns such as restoration speed.

We adopt 2 randomized traffic distribution models:

1. The number of spare wavelengths on each link follows normal distribution, with the variance being 1.5, 2.0 or 2.5.
2. The number of spare wavelengths on each link follows uniform distribution.

We make up the above two traffic models by making use of the two most commonly used random distributions: normal distribution and uniform distribution. The sample networks we use are USA long haul network and France Telecom network, the same networks we have used in Chapter 3 and Chapter 4. Each sample point in our performance curves is the mean of 100 simulations under the same condition. For both normal and uniform traffic distributions, the interested region of network-wise ratio of working/spare wavelengths is still between 1 and 2, the reason for which has been given in Section 2.2.

Some performance figures are given below to capture the performance of 3 rerouting approaches, under different traffic conditions.

Fig. 5.9 presents the restorability performances of the 3 rerouting approaches for the USA network, when the number of spare wavelengths on each link follows a normal distribution with a variance of 1.5. It can be seen that the mean restorability appears to decrease linearly as the mean working over spare ratio increases. The approach of rerouting using the whole network graph has the best performance as expected, while the approach using DRR path set and greedy heuristic has the worst performance.

In Fig. 5.10, we compare the restorability performances of the 3 rerouting approaches using the France network, and we observe similar relationship between mean restorability and the mean working over spare ratio. However all three approaches have a lower mean restorability, and the difference between the best and the worst approach appears to be bigger.

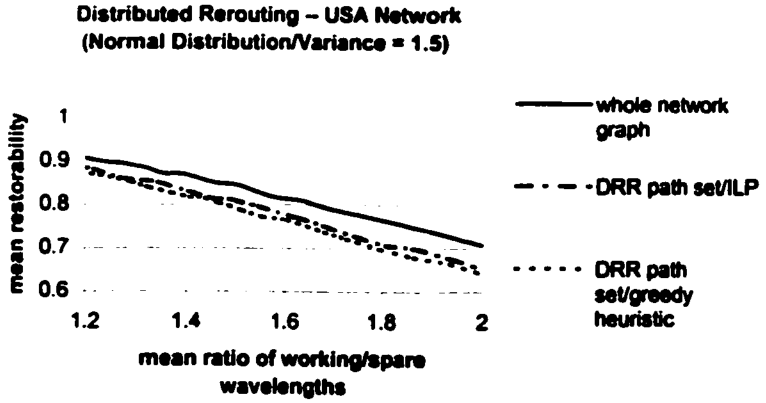


Fig. 5.9 Restorability Performance of Various Distributed Rerouting Algorithms: USA Network, Normal Distribution with Variance = 1.5

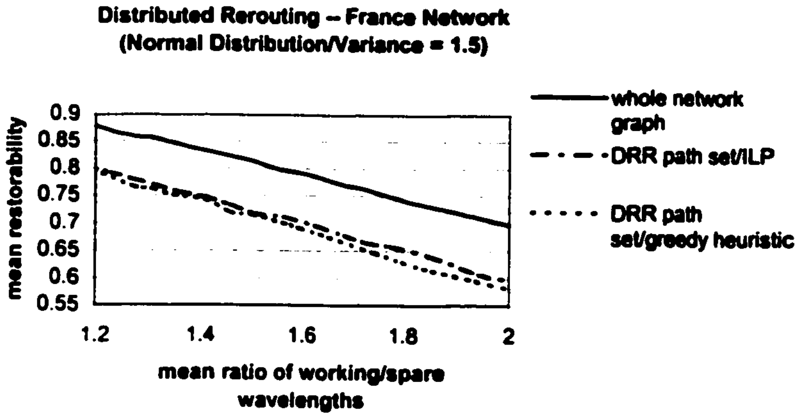


Fig. 5.10 Restorability Performance of Various Distributed Rerouting Algorithms: France Network, Normal Distribution with Variance = 1.5

We have repeated the comparison using a variance of 2.0 (Fig. 5.11 for the USA network and Fig. 5.12 for the France network), and a variance of 2.5 (Fig. 5.13 for the USA network and Fig. 5.14 for the France network). We observe that the larger the variance, the lower is the mean restorability. This is because the rerouting capability of an end-to-end path is determined by the link with the minimum spare capacity along the path, and the larger the variance, the lower is that minimum spare capacity.

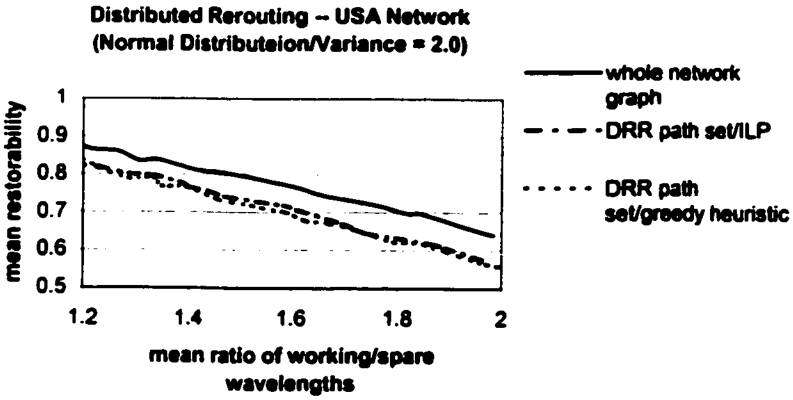


Fig. 5.11 Restorability Performance of Various Distributed Rerouting Algorithms: USA Network, Normal Distribution with Variance = 2.0

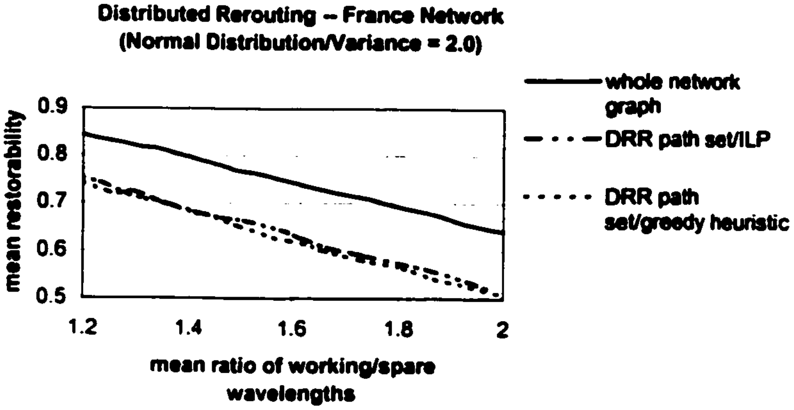


Fig. 5.12 Restorability Performance of Various Distributed Rerouting Algorithms: France Network, Normal Distribution with Variance = 2.0

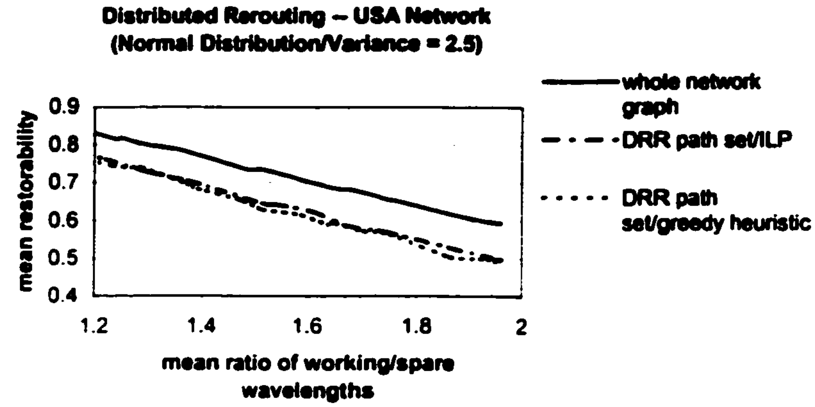


Fig. 5.13 Restorability Performance of Various Distributed Rerouting Algorithms: USA Network, Normal Distribution with Variance = 2.5

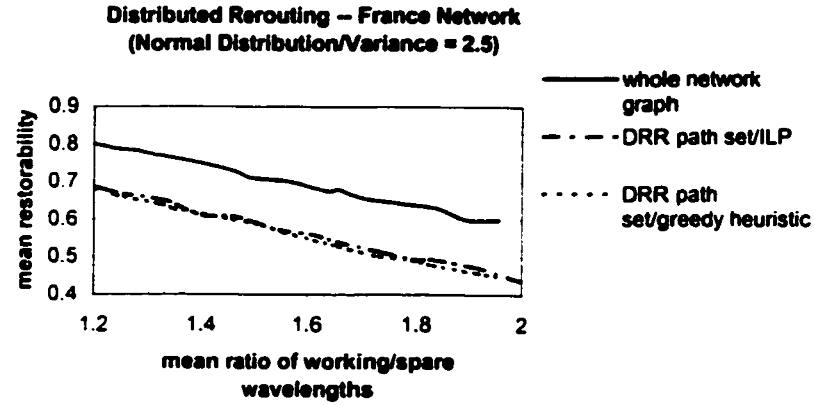


Fig. 5.14 Restorability Performance of Various Distributed Rerouting Algorithms: France Network, Normal Distribution with Variance = 2.5

We have also make the comparison using a different distribution, i.e., the uniform distribution in Fig. 5.15 and Fig. 5.16. We observe that under the same working over spare ratio, the mean restorability of a given network under uniform distribution appears to be better than the mean restorability under normal distributions.

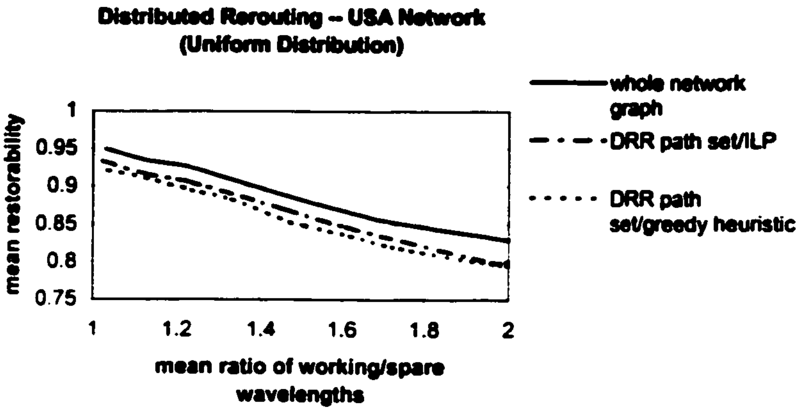


Fig. 5.15 Restorability Performance of Various Distributed Rerouting Algorithms: USA Network, Uniform Distribution

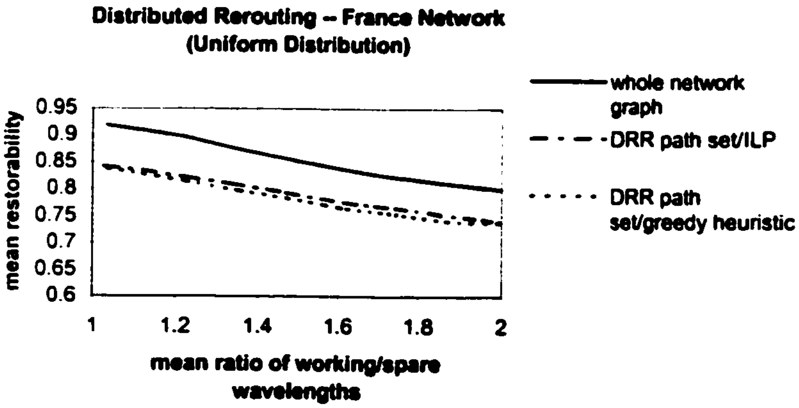


Fig. 5.16 Restorability Performance of Various Distributed Rerouting Algorithms: France Network, Uniform Distribution

In Fig. 5.17 below we provide examples on the 95% confidence interval of restorabilities from USA network, when normal distribution variance equals to 1.5. We see that the confidence intervals between the upper and lower bounds are quite small compared with the means. Although not shown, we have similar observations for other experimental data. That justifies our method to obtain one sample point from the average of 100 simulation results under the same condition.

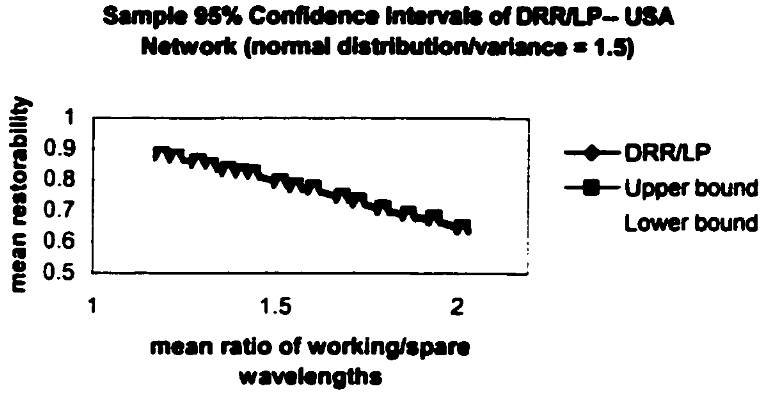


Fig. 5.17 Example 95% Confidence Intervals

5.3.1 Discussions

From our simulation figures, two important observations can be made:

1. The restoration performance of DRR/ILP is pretty close to MRF based on the whole network graph, which is the theoretical upper bound for any link restoration approach. The restorability degradation of DRR/ILP relative to the theoretical upper bound is roughly between 3% ~ 15%, under our simulation conditions. That is quite a satisfactory performance in engineering, considering the fact that the DRR rerouting path set for each link is small, and the theoretical upper bound based on the whole network graph can hardly be achieved. With such results, we justify that P-cycle is a highly efficient topological pattern for link protection/restoration. Also we believe the straddling link ring-finding algorithm can provide enough link restoration paths for a sparse mesh network, when being executed in the distributed manner as we proposed.
2. We find that the performance difference between DRR/greedy heuristic and DRR/ILP is very small (less than 2%), which is a nice surprise. We know that link restoration with DRR path set is a linear optimization problem, and the maximum rerouting flow is obtained by solving it with an ILP tool. On the other hand, the greedy heuristic in general is not an optimum solution. We give in Fig. 5.18 below a special case where the greedy heuristic fails to obtain the optimum solution. The topological pattern in Fig. 5.18 is referred to as the 'trap topology' [44].

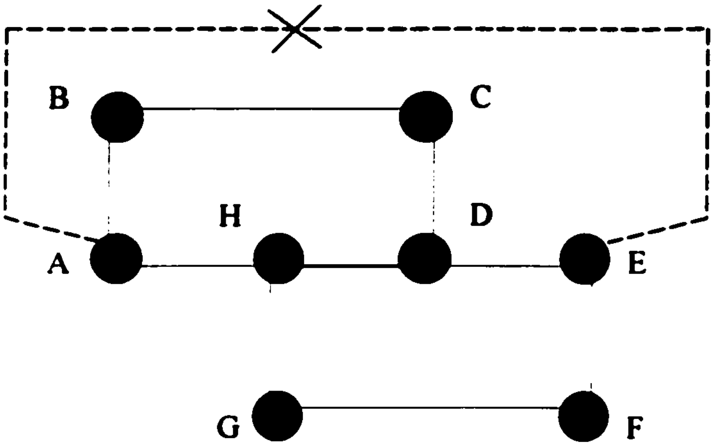


Fig. 5.18 Trap Topology

In Fig. 5.18, the failed link is A-E, and all the other links have the same spare capacity, say k. The DRR path set includes Path1 = A-H-D-E, Path2 = A-B-C-D-E and Path3 = A-H-G-F-E. The greedy heuristic will only get a rerouting flow of k units by using Path1, because both Path2 and Path3 are then blocked. Actually the maximum rerouting flow in this case is 2k units, which is achieved by routing k units of flow over Path2 and Path3 respectively.

It has been proved [44] that the trap topology and its variations are improbable to form in sparse mesh networks, whose average nodal degrees are between 2 ~ 4. We come up with such a hypothesis to explain the close to optimum performance of the greedy heuristic: the greedy heuristic is optimum except for the trap topology and its variations, which are rarely found in sparse mesh networks. More analytical work is needed to testify the hypothesis.

The traffic distribution models we have used so far are all based on generating random number of working/spare wavelengths on each link independently. This allows us a simple and more efficient way to study the rerouting performances of various algorithms/protocols. On the other hand, we need to further verify the performances of our rerouting algorithms/protocols under various end-to-end traffic models.

We pick the USA network and setup the end-to-end traffic as follows:

1. First we route the following 22 pairs of end-to-end traffic one by one across the network:

   Node 1 to node 7,

   Node 2 to node 8,

   ...

   Node 22 to node 28.

Each traffic pair takes the shortest path between two end nodes, with a normally distributed capacity, whose mean equals to half of the minimum number of spare wavelengths along the path and variance equals to 2.0.

2. Then we route the following 26 pairs of end-to-end traffic one by one across the network:

   Node 1 to node 3,

   Node 2 to node 4,

   ...

   Node 26 to node 28.

Similarly, Each traffic pair takes the shortest path between two end nodes, with a normally distributed capacity, whose mean equals to half of the minimum number of spare wavelengths along the path and variance equals to 2.0.

The distributed rerouting performances of various algorithms/protocols under such an end-to-end traffic model are given in Fig. 5.19 below. We find in Fig. 5.19 that DRR path set/ILP still performs very close to the maximum rerouting flow with the whole network graph, and DRR path set/greedy heuristic still performs very close to DRR path set/ILP.

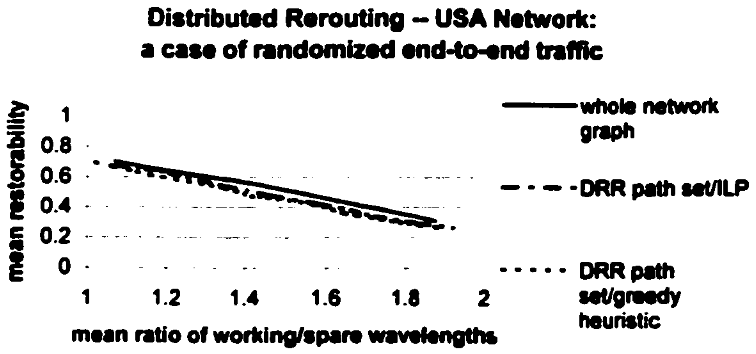


Fig. 5.19 Distributed Rerouting -- USA Network: A Case of Randomized End-to-end Traffic

5.4 Concluding Remarks

In this chapter we propose a distributed ring-based rerouting protocol (DRR), which adopts some good ideas from previous work, such as distributed pre-failure planning, decoupling the topology factor from the traffic distribution factor. The new idea in our DRR protocol is that in a wavelength routing network, a ring or P-cycle topology should be decomposed into link restoration paths, instead of used as a whole self-healing ring (as in the case of static WDM ring cover).

The near-optimum rerouting performance of the DRR protocol justifies previous theoretical studies on P-cycle [22,23,34], which argue that the P-cycle topology is as efficient as mesh topology in link protection/restoration. Also we believe that the protection efficiency of the P-cycle topology can be best exploited when it is applied to routing networks such as wavelength routing networks, where protection bandwidth can be shared at the WDM layer.

We mention from time to time that the DRR protocol is based on the wavelength routing and distribution protocols, which are intended as the enabling techniques for a scalable WDM layer. It would be fair to say that the DRR protocol is an indispensable part of the wavelength routing protocol, since protection/restoration is one of the key functionalities of the WDM layer. The consistency between the DRR protocol and the whole scalable WDM layer can be find within various features of the DRR protocol, such as the sharing of restoration topologies in the ring-finding stage, localized rerouting table update, localized link restoration by using the DRR path set only.

Finally, we observe that the overhead introduced by the DRR protocol is moderate, because the protocol is based on a scalable set of ring/cycles found by the straddling link algorithm.

Chapter 6

Design Guidelines and Recommendations

In this chapter, we give some design guidelines and recommendations on the implementation of the straddling link algorithm (SLA) in WDM networks.

The SLA algorithm is a specified ring-finding algorithm for network protection/restoration with ring and P-cycle topologies. The flow diagram of the centralized (or offline) version of the SLA algorithm is shown in Fig. 3.8, while the distributed (or dynamic) version of the SLA algorithm is proposed in Sections 5.1 and 5.2 as a protocol.

The SLA algorithm works best for sparse mesh networks of average nodal degrees around 3, since the way it works is by investgating those links whose two end nodes are both of degree 3 or higher. So in general, the sparser the network, the smaller is the SLA ring set. As the average nodal degree of a network increases, the SLA ring set also gets larger but is still considered scalable, because the number of rings is upper-bounded by the number of links.

Although the SLA algorithm has a good link coverage performance in general, there is no guarantee that all those links coverable by at least one ring (link-survivable) can be covered by the SLA ring set. Whereas we do not have a general rule of thumb of durable topologies, our experience allows us to make the following recommendations. One should avoid the special topology where a ring is connected to the rest of the network through a cut edge (Ref: Section 3.3.1) In a case where a link is survivable but not covered by the SLA ring set, we can take the following simple patching approach: merge the link itself with the second shortest path between the two end nodes to form a covering ring.

Based on the experience from our study, we would recommend that the distributed version of the SLA be implemented in networks that support wavelength routing. To implement the dynamic SLA protocol in a wavelength routing network, the major extension that should be made to the wavelength routing protocol (WRP) is: one of the end nodes of a link of type 1(a) or 1(b) (refer to Section 3.1) manages the topology information of the cycle found from the link, so that the cycle topology can be decomposed into rerouting paths for the links along or straddling the ring. Such an extension does not introduce significant complexities on top of the WRP protocol. When a link failure does occur, the capacities of the pre-planned rerouting paths can be decided either by linear programming or greedy heuristic (refer to Section 5.2.2). The linear programming based approach is optimum but relatively complicated, while the greedy heuristic based approach is sub-optimum but requires much less computation.

For static WDM networks, we would use the centralized SLA algorithm to find a set of link-covering rings, so that those rings can then be configured as logical self-healing rings to protect static end-to-end traffic. In general, we would recommend the centralized SLA for networks with average nodal degrees around 3. As the average nodal degree of a network increases, the SLA will find a larger set of rings and therefore one should expect the algorithm to take more time to execute. We recommend that the SLA ring set be used in pure ring cover manner, because the restorability performance of P-cycle cover over pure ring cover is very trivial compared with the complexities that come along.

Chapter 7

Conclusion

In this thesis we have clarified the differences between the protection/restoration models of static WDM networks and wavelength routing networks, depending on whether protection bandwidth can be shared or not, at the DWDM layer. Then we propose the straddling link ring finding algorithm, which emphasis more on scalability and ease of implementation, rather than the guarantee of 100% link coverage. We proceeded further with the ring set found by the straddling link algorithm to analyze the protection/restoration issues in static WDM networks and wavelength routing networks. Our experience demonstrates that distributed ring-based rerouting (DRR) is the way P-cycle topologies should be used for WDM network protection/restoration.

Based on the works above, we realize that WDM layer protection/restoration in real world networks should be 'best-effort' instead of guaranteed. From the performance figures in Chapter 5, we find that even with maximum rerouting flow method, it is still hard to achieve 100% network-wise restorability, which requires perfect combination of the topology factor and the traffic distribution factor. Therefore the DRR protocol can be used in the best-effort link protection/restoration approach, although it performs quite close to the theoretical upper bound.

7.1 Future work

The following are some interesting aspects worthy of further investigation:

1. Analytical studies on the comparison between DRR/greedy heuristic and DRR/ILP.
2. Both simulation and analytical studies on the performance of the DRR protocol under various end-to-end traffic models.
3. Both simulation and analytical studies on the graphical features that make the same rerouting algorithm perform differently in different networks. That performance difference cannot be simply explained by the difference in the average nodal degree.
4. Restoration speed is an important issue that hasn't been addressed in this thesis. We know that in optical WDM networks, restoration speed is mainly decided by the signaling stage to setup restoration paths, instead of by the optical space switching stage. Our DRR protocol should be

fast because it adopts pre-failure planning. On the other hand, it is still hard to give an accurate estimation on the restoration speed the DRR protocol can achieve, because in the restoration stage of the DRR protocol, we need to use the wavelength distribution protocol to setup rerouting lightpaths, and the wavelength distribution protocol is still being prototyped. So the research on restoration speed should be ongoing along with the development in the wavelength distribution protocol.

5. Studies on the correlation between WDM layer protection/restoration and WDM layer traffic engineering [4,6] and traffic grooming [4,6].

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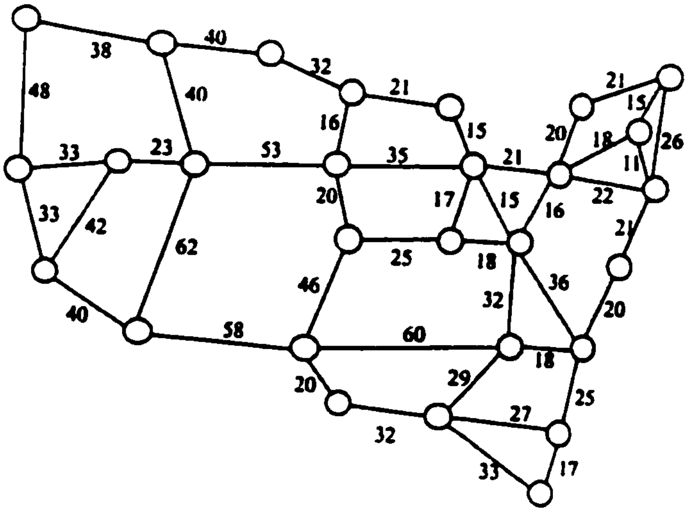
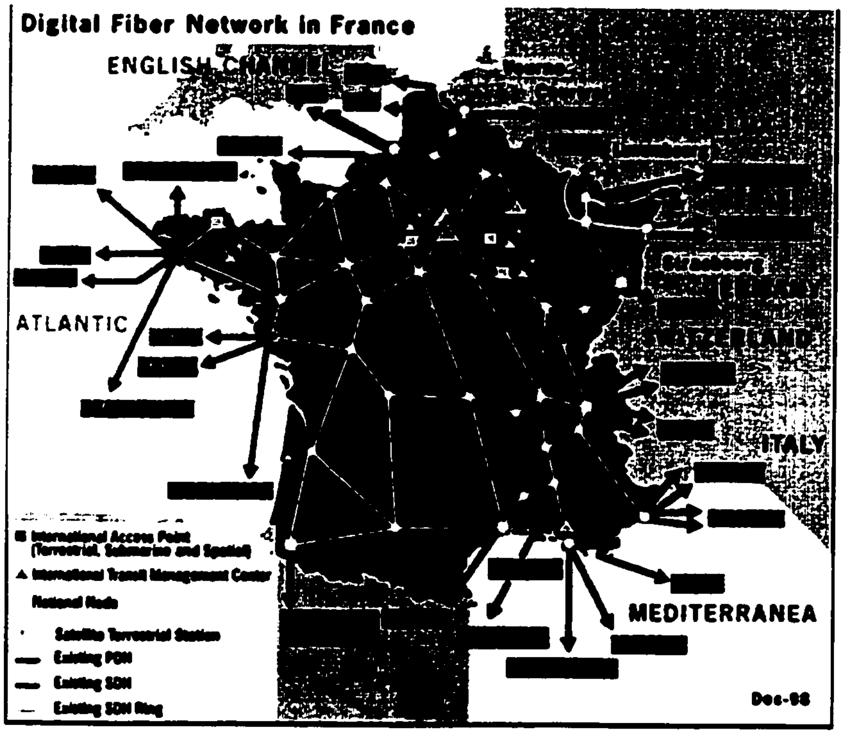
[51] "IIJ Homepage", http://www.iij.ad.jp/network/index02-e.html

Appendix I Topologies of Sample Networks

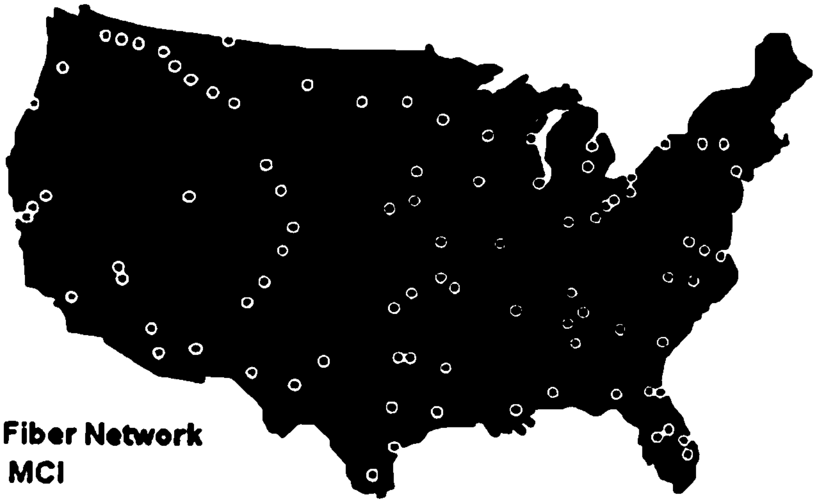
(a) Topology of USA Long Haul Network [47]



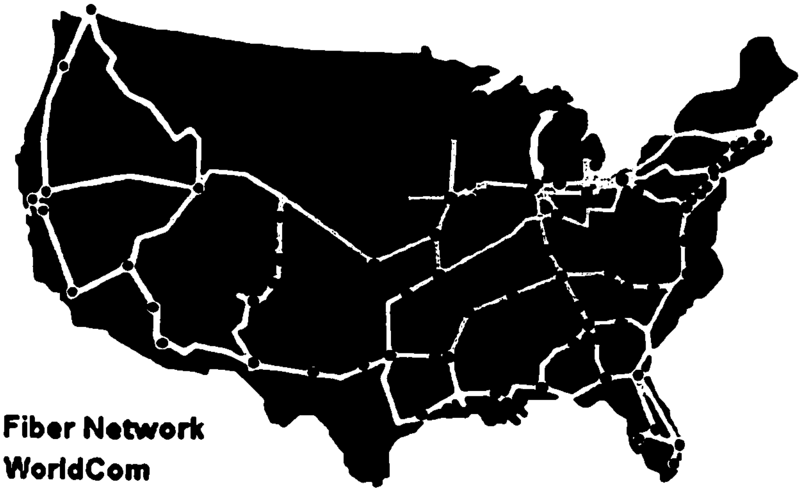
(b) Topology of France Telecom Network [48]



(c) Topology of MCI Fiber Network [49]



(d) Topology of WorldCom Fiber Network [50]



(e) Topology of Japan Fiber Network [51]

Appendix II Snif Files of Sample Networks

A '.snif' file describes the node to link adjacency relationships between the nodes and spans (links) in a network graph. For example, from the '.snif' file of USA long haul network, we can see that there are 28 nodes in the network; span 1 connects nodes 1 and 2, span 2 connects nodes 1 and 5. The 'XCoord' and 'Ycoord' columns are never used. In our simulations in this thesis, the 'distance' columns in '.snif' files are unused, because the distance between nodes is counted by the number of hops, not physical distances. The 'working' and 'spare' columns are not used either, because in our simulations, the numbers of working/spare wavelengths on each link are randomly generated, instead of being hard-coded in '.snif' files.

(a) USA Long Haul Network

Date: 20-June-01
File Name: usa.snif
Network: USA Long Haul

Node	XCoord	YCoord
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0

28	0	0

Span	NodeA	NodeB	Distance	Working	Spare
1	1	2	1	2	0
2	1	5	1	2	0
3	2	3	1	2	0
4	2	7	1	2	0
5	3	4	1	2	0
6	4	8	1	2	0
7	4	13	1	2	0
8	5	6	1	2	0
9	5	9	1	2	0
10	6	7	1	2	0
11	6	9	1	2	0
12	7	8	1	2	0
13	7	10	1	2	0
14	8	12	1	2	0
15	8	14	1	2	0
16	9	10	1	2	0
17	10	11	1	2	0
18	11	12	1	2	0
19	11	22	1	2	0
20	11	25	1	2	0
21	12	15	1	2	0
22	13	14	1	2	0
23	14	15	1	2	0
24	14	16	1	2	0
25	14	21	1	2	0
26	15	21	1	2	0
27	16	17	1	2	0
28	16	19	1	2	0
29	16	20	1	2	0
30	17	18	1	2	0
31	18	19	1	2	0
32	18	20	1	2	0
33	19	20	1	2	0
34	20	24	1	2	0
35	21	22	1	2	0
36	21	23	1	2	0
37	22	23	1	2	0
38	22	26	1	2	0
39	23	24	1	2	0
40	23	27	1	2	0
41	25	26	1	2	0
42	26	27	1	2	0
43	27	28	1	2	0
44	26	28	1	2	0

(b) France Telecom Network

Date: 20-June-01
File Name: france.snif
Network: France Telecom
Node XCoord YCoord

1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0
28	0	0
29	0	0
30	0	0
31	0	0
32	0	0
33	0	0
34	0	0
35	0	0
36	0	0
37	0	0
38	0	0
39	0	0
40	0	0
41	0	0
42	0	0
43	0	0
44	0	0

Span	**NodeA**	**NodeB**	**Distance**	**Working**	**Spare**
1	1	2	1	2	0
2	1	3	1	2	0
3	2	3	1	2	0
4	2	18	1	2	0
5	3	19	1	2	0
6	2	4	1	2	0
7	2	5	1	2	0
8	5	8	1	2	0
9	8	9	1	2	0
10	9	10	1	2	0

11	10	11	1	2	0
12	11	12	1	2	0
13	7	8	1	2	0
14	7	6	1	2	0
15	4	6	1	2	0
16	4	17	1	2	0
17	12	13	1	2	0
18	7	13	1	2	0
19	13	15	1	2	0
20	14	15	1	2	0
21	15	16	1	2	0
22	16	17	1	2	0
23	17	18	1	2	0
24	18	19	1	2	0
25	19	20	1	2	0
26	19	22	1	2	0
27	17	22	1	2	0
28	17	36	1	2	0
29	15	35	1	2	0
30	36	37	1	2	0
31	15	38	1	2	0
32	14	38	1	2	0
33	14	39	1	2	0
34	39	40	1	2	0
35	40	41	1	2	0
36	40	42	1	2	0
37	41	42	1	2	0
38	41	43	1	2	0
39	42	43	1	2	0
40	42	34	1	2	0
41	34	35	1	2	0
42	37	35	1	2	0
43	35	36	1	2	0
44	36	22	1	2	0
45	35	23	1	2	0
46	36	28	1	2	0
47	22	23	1	2	0
48	23	21	1	2	0
49	20	21	1	2	0
50	21	26	1	2	0
51	25	26	1	2	0
52	24	25	1	2	0
53	24	21	1	2	0
54	23	24	1	2	0
55	23	27	1	2	0
56	24	27	1	2	0
57	27	28	1	2	0
58	35	28	1	2	0
59	28	29	1	2	0
60	29	30	1	2	0
61	35	33	1	2	0
62	33	34	1	2	0
63	32	34	1	2	0
64	33	32	1	2	0
65	30	33	1	2	0
66	30	31	1	2	0

67	31	32	1	2	0
68	37	38	1	2	0
69	38	39	1	2	0
70	44	32	1	2	0

(C) MCI Network

Date : 21-Jun-01
File Name: mci.snif
Network: MCI

Node	XCoord	YCoord
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0
28	0	0
29	0	0
30	0	0
31	0	0
32	0	0
33	0	0
34	0	0
35	0	0
36	0	0
37	0	0
38	0	0
39	0	0
40	0	0
41	0	0

Span	NodeA	NodeB	Distance	Working	Spare
1	1	2	1	2	0
2	1	4	1	2	0
3	4	5	1	2	0
4	5	6	1	2	0
5	3	4	1	2	0
6	2	3	1	2	0
7	2	27	1	2	0
8	3	26	1	2	0
9	3	11	1	2	0
10	9	10	1	2	0
11	8	9	1	2	0
12	6	8	1	2	0
13	7	8	1	2	0
14	4	8	1	2	0
15	7	6	1	2	0
16	10	11	1	2	0
17	9	11	1	2	0
18	11	12	1	2	0
19	13	11	1	2	0
20	14	13	1	2	0
21	15	12	1	2	0
22	12	23	1	2	0
23	22	23	1	2	0
24	22	25	1	2	0
25	23	24	1	2	0
26	24	25	1	2	0
27	24	26	1	2	0
28	26	27	1	2	0
29	27	28	1	2	0
30	28	29	1	2	0
31	28	30	1	2	0
32	29	30	1	2	0
33	30	40	1	2	0
34	31	40	1	2	0
35	31	25	1	2	0
36	25	30	1	2	0
37	31	20	1	2	0
38	20	32	1	2	0
39	20	21	1	2	0
40	15	21	1	2	0
41	14	16	1	2	0
42	16	17	1	2	0
43	16	18	1	2	0
44	17	18	1	2	0
45	16	19	1	2	0
46	19	32	1	2	0
47	19	34	1	2	0
48	32	33	1	2	0
49	33	34	1	2	0
50	34	35	1	2	0
51	33	36	1	2	0
52	35	41	1	2	0
53	35	36	1	2	0
54	41	37	1	2	0

55	36	37	1	2	0
56	35	37	1	2	0
57	37	40	1	2	0
58	39	40	1	2	0
59	38	39	1	2	0
60	37	38	1	2	0

(d) WorldCom Network

Date: 21-Jun-01
File Name: worldcom.snif
Network: WorldCom

Node	XCoord	YCoord
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0

Span	NodeA	NodeB	Distance	Working	Spare
1	1	4	1	2	0
2	1	2	1	2	0
3	4	2	1	2	0
4	2	3	1	2	0
5	3	4	1	2	0
6	5	3	1	2	0
7	5	6	1	2	0
8	5	11	1	2	0
9	6	9	1	2	0
10	6	7	1	2	0

11	7	8	1	2	0
12	6	8	1	2	0
13	6	10	1	2	0
14	9	10	1	2	0
15	10	18	1	2	0
16	9	18	1	2	0
17	18	19	1	2	0
18	17	19	1	2	0
19	19	20	1	2	0
20	17	20	1	2	0
21	11	17	1	2	0
22	16	20	1	2	0
23	20	22	1	2	0
24	22	23	1	2	0
25	21	22	1	2	0
26	21	15	1	2	0
27	24	21	1	2	0
28	23	24	1	2	0
29	23	25	1	2	0
30	24	25	1	2	0
31	24	26	1	2	0
32	25	26	1	2	0
33	14	15	1	2	0
34	13	14	1	2	0
35	11	13	1	2	0
36	12	16	1	2	0
37	12	13	1	2	0
38	13	27	1	2	0
39	4	13	1	2	0
40	4	12	1	2	0
41	4	27	1	2	0

(e) Japan Network

Date : 21-May-01
File Name: japan.snif
Network: Japan

Node	XCoord	YCoord
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0

16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0
25	0	0
26	0	0
27	0	0
28	0	0
29	0	0
30	0	0
31	0	0
32	0	0
33	0	0
34	0	0
35	0	0
36	0	0
37	0	0
38	0	0
39	0	0
40	0	0
41	0	0
42	0	0
43	0	0
44	0	0
45	0	0
46	0	0
47	0	0
48	0	0
49	0	0
50	0	0
51	0	0
52	0	0
53	0	0
54	0	0
55	0	0
56	0	0

Span	NodeA	NodeB	Distance	Working	Spare
1	1	2	1	2	0
2	1	3	1	2	0
3	3	5	1	2	0
4	2	5	1	2	0
5	2	6	1	2	0
6	5	6	1	2	0
7	3	4	1	2	0
8	4	6	1	2	0
9	6	13	1	2	0
10	5	7	1	2	0
11	7	11	1	2	0
12	13	14	1	2	0
13	14	17	1	2	0

14	14	15	1	2	0
15	15	17	1	2	0
16	15	16	1	2	0
17	16	17	1	2	0
18	16	18	1	2	0
19	17	12	1	2	0
20	17	18	1	2	0
21	12	18	1	2	0
22	11	12	1	2	0
23	8	9	1	2	0
24	9	10	1	2	0
25	10	12	1	2	0
26	10	18	1	2	0
27	10	19	1	2	0
28	18	19	1	2	0
29	18	21	1	2	0
30	17	24	1	2	0
31	16	25	1	2	0
32	24	25	1	2	0
33	24	26	1	2	0
34	21	24	1	2	0
35	21	22	1	2	0
36	22	24	1	2	0
37	23	24	1	2	0
38	22	23	1	2	0
39	23	38	1	2	0
40	24	38	1	2	0
41	24	33	1	2	0
42	26	27	1	2	0
43	25	26	1	2	0
44	19	20	1	2	0
45	20	41	1	2	0
46	40	41	1	2	0
47	39	40	1	2	0
48	36	39	1	2	0
50	36	37	1	2	0
51	34	37	1	2	0
52	27	28	1	2	0
53	28	29	1	2	0
54	29	30	1	2	0
55	30	32	1	2	0
56	32	33	1	2	0
57	31	32	1	2	0
58	31	33	1	2	0
59	33	34	1	2	0
60	33	35	1	2	0
61	34	35	1	2	0
62	35	36	1	2	0
63	36	43	1	2	0
64	35	43	1	2	0
65	40	42	1	2	0
66	43	45	1	2	0
67	31	46	1	2	0
68	42	44	1	2	0
69	44	47	1	2	0

70	44	56	1	2	0
71	44	45	1	2	0
72	45	56	1	2	0
73	46	56	1	2	0
74	42	48	1	2	0
75	42	51	1	2	0
76	48	49	1	2	0
77	47	48	1	2	0
78	49	50	1	2	0
79	51	52	1	2	0
80	50	53	1	2	0
81	50	56	1	2	0
82	55	56	1	2	0
83	54	55	1	2	0
84	53	54	1	2	0
85	52	53	1	2	0

Appendix III The Operations of Self-healing Rings (SHR)

Self-healing rings (SHR) can be categorized according to the following two criteria:

1. Path restoration or link restoration
2. Unidirectional or bi-directional

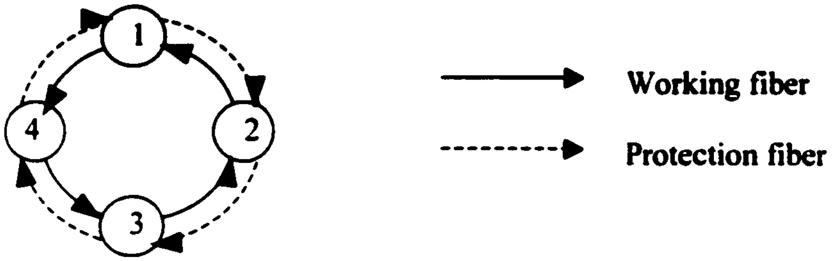
A SHR is called a unidirectional SHR if its duplex channels travel over opposite directions around the ring, and a SHR is called a bi-directional SHR if its duplex channels travel over the same direction around the ring.

Although there are 4 permutations in total, only 2 logical types are commercially available: unidirectional path protection switching rings (UPSR) and bi-directional link protection switching rings (BLSR). A BLSR may use four fibers or two fibers depending on the spare capacity arrangement. For convenience, a BLSR with 4 fibers and a BLSR with 2 fibers are denoted by BLSR/4 and BLSR/2 respectively. BLSR/2 operates logically in the same way as BLSR/4 except the timeslots/wavelengths on each fiber are divided into working and protection channels. We introduce the principles of UPSR, BLSR/4 and BLSR/2 in the following respectively.

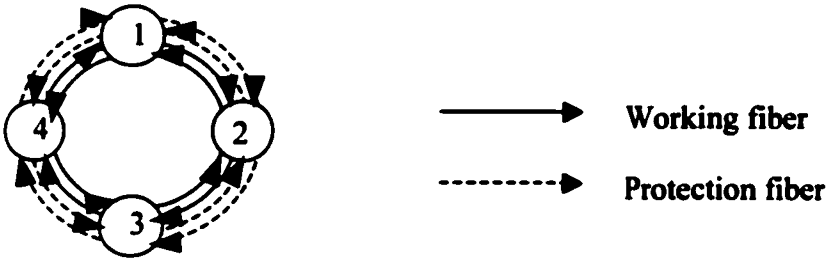
The architectures of UPSR, BLSR/4 and BLSR/2 are shown in the figure below. Each of the numbered nodes symbolizes an add-drop-multiplexer (ADM), either TDM or WDM based.

The UPSR architecture uses two fibers (one for working and the other for protection), and is based on 1+1 protection. During normal operation, a duplicate copy of the working signal is sent the other way around the ring. The destination node monitors the quality of the 2 signals received and selects the better one. Therefore there is a 100% bandwidth redundancy in UPSR rings, and a UPSR is also known as a 'dedicated protection ring'.

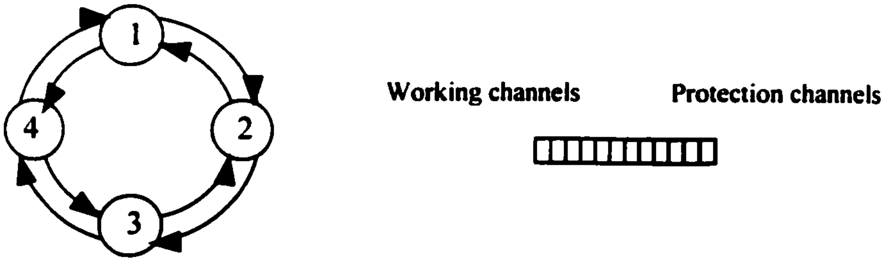
Unlike a UPSR, in a BLSR (either 4 or 2 fibers) restoration is done by looping back the working signal from the working fiber (or working channel in BLSR/2) to the protection fiber (or protection channel in BLSR/2) at the nodes adjacent to the failed segment. In a BLSR, there is no dedicated protection path (as in a UPSR), but a pool of spare bandwidths that are shared amongst multiple working paths. Therefore a BLSR is also known as a 'shared protection ring'. A BLSR can be designed in that way that all traffic demands are served and protected, while the bandwidth redundancy is lower then using UPSR. On the other hand, in a BLSR restoration is performed at both nodes adjacent to a failed segment, thus signaling is needed to coordinate the protection switching. As a result the ADMs used in a BLSR are more complex and expensive than those used in a UPSR.



(a) UPSR



(b) BLSR/4



(c) BLSR/2

Fig. III.1 UPSR, BLSR/4 and BLSR/2

Appendix IV Binary Heap Implementation of Dijkstra's Algorithm [40]

We would like to implement Dijkstra's algorithm using a binary heap. In this algorithm heap H would be the collection of nodes with finite temporary distances while the key of a node would be its temporary distance. The following subroutines are needed to carry on the algorithm:

create-heap(H): create an empty binary heap.
find-min(i, H): find and return a node i of minimum key.
insert(i, H): insert a new node i with a predefined key.
decrease-key(value, i, H): deduce the key of node i by 'value'.
delete-min(i, H): delete a node i of minimum key.

```
heap-Dijkstra algorithm;
begin
    create-heap(H);
    d(j) := $\infty$ for all j $\in$ N;
    d(s) := 0 and pred(s) := 0;
    insert(s, H);
    while H $\neq \emptyset$ do
    begin
        find-min(i H);
        delete-min(i H);
        for each (i, j) $\in$ A(i) do
        begin
            value := d(i) + $C_{ij}$;
            if d(j) > value then
                if d(j) = $\infty$ then d(j) := value, pred(j) := i, and insert(j, H);
                else set d(j) := value, pred(j) := i, and decrease-key(value, i, H)
        end;
    end;
end;
```

Fig. IV.1 Dijkstra's Algorithm Using a Binary Heap

The above figure provides the complete pseudo codes of heap-Dijkstra's algorithm.