Design and analysis of P-cycle-based survivable optical networks

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Design and Analysis of P-Cycle-Based Survivable Optical Networks

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School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

2006-4-30

Date

A handwritten signature in black ink, appearing to read 'Zhang Zhenrong', written in a cursive style.

Zhang Zhenrong

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Summary

In future high-capacity wavelength division multiplexed (WDM) optical networks, the failure of a network component such as a fiber link can lead to the failure of all lightpaths that traverse the failed link. Since each lightpath is expected to operate at a rate of several Gbps, such a failure can lead to a severe disruption in the network's traffic. So it is critically important to design WDM optical networks that are inherently fault-tolerant against events such as fiber cable cuts, central office failures and hardware failures. A survivable WDM optical network can provide alternate routes between a pair of nodes in case of failures. The primary objective of network survivability is to maintain the end-to-end data service in the event of any network element failures such as link or node failures.

Survivability in the optical network involves detecting any network element failure and performing a protection switching to divert the traffic through an alternate path. There have been two basic survivability approaches in optical networks, namely (a) protection and (b) restoration. The protection approach pre-determines backup paths and reserve resources at the same time when the corresponding working lightpaths are established. With the restoration approach, a search is initiated to find backup paths only at the time when a failure occurs in the network. The protection approach can guarantee the recovery of failed lightpaths and its recovery speed is fast, and hence it is attractive for guaranteed services. The restoration approach may consume less spare capacity, but it cannot guarantee successful recovery and may take a much longer time for recovery.

In this thesis, we focus on the protection approach for survivability in the optical layer, in particular, the method of pre-configured protection-cycle (p -cycle). The p -cycle method can provide ring-like fast protection and mesh-like high efficiency in the use of spare capacity. We have proposed a new design heuristic, i.e., the *efficiency-ratio (ER) based unity- p -cycle* design, for p -cycle based survivable WDM networks design without using the integer linear programming (ILP). Computer simulations have been conducted to evaluate the performance of this design heuristic, where four typical networks have been investigated. It is shown that the results of our algorithm are very close to the optimal solution using the ILP. We have extended the *ER-based unity- p -cycle design* heuristic to design survivable networks where traffic demand is not static but dynamically changing, and have proposed three different strategies to dynamically configure p -cycles that are adaptive to changing traffic demands. Our simulation studies have shown that dynamic p -cycle-based designs can achieve very good blocking performance comparable to that of the shared backup path protection scheme but with a much faster restoration speed.

Aiming at simplifying network management and reducing processing overhead, we have considered the problem of dynamically survivable WDM networks with a protected working capacity envelope (PWCE). We have developed a modified new ILP model to determine the protected working capacity envelope and carried out computer simulations to evaluate the blocking performance. To further improve the efficiency in the use of spare capacity for survivable WDM optical networks, we have proposed a new approach called shared p -cycles design. An ILP formulation has been developed to solve the shared p -cycles design problem for both wavelength

convertible and non-convertible optical networks. To compare with the conventional unshared p -cycles design, computer simulation has been conducted where four different test networks have been investigated.

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List of Acronyms

Abbreviations	Full Expressions
AE	Apriori Efficiency
ASE	Amplified Spontaneous Emission
ATM	Asynchronous Transmission Mode
BGP-4	Border Gateway Protocol-4
BLSR	Bi-directional Line Switched Ring
CR-LDP	Constraint-based Label Distribution Protocol
CDM	Code Division Multiplexing
ECMF	Equal Cost Multipath Forwarding
EDFA	Erbium Doped Fiber Amplifier
ER	Efficiency Ratio
FDM	Frequency Division Multiplexing
FEC	Forwarding Equivalence Class
FIR	Full Information Routing
FIS	Failure Indication Signal
FRS	Failure Recovery Signal
GMPLS	General Multi Protocol Switch
ILP	Integer Linear Programming
ICMP	Internet Control Message Protocol
LSA	Link State Advertisement
LSP	Label Switched Path
LSR	Label Switched Router
MEMS	Micro-Electro-Mechanical-Systems

MPLS	Multiprotocol Label Switching
OADM	Optical Add Drop Multiplexer
OSPF	Open Shortest Path First
OXC	Optical Cross-Connect
<i>p</i> -Cycle	Preconfigured Protection Cycle
PML	Path Merge LSR
PSL	Path Switched LSR
PWCE	Protected Working Capacity Envelope
ROADM	Reconfigurable Optical Add Drop Multiplexer
RSVP	Resource-Reservation Protocol
RWA	Routing and Wavelength Assignment
SBPP	Shared Backup Path Protection
SCA	Spare Capacity Assignment
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
TS	Topological Score
VWP	Virtual Wavelength Path
WADM	Wavelength Add Drop Multiplexer
WDM	Wavelength Division Multiplexing
WIXC	Wavelength Interchanging Cross-Connect
WP	Wavelength Path
WSXC	Wavelength Selective Cross-Connect
WXC	Wavelength Cross-Connect

Chapter 1 Introduction

1.1 Background

Telecommunication networks and the traffic they carry are experiencing explosive growth everywhere in the world today. The Internet is developing rapidly with its ultimate goal being to provide us with easy and fast access to any desired information from anywhere in the world. Information exchange (or telecommunications) technology, which has been evolving continuously since the time the telephone was invented, is still striving to meet the users' demands for higher and higher bandwidth. This demand is attributed to the growing popularity of bandwidth-intensive networking applications, such as data browsing on the World Wide Web (WWW), java applications, video conferencing, interactive distance learning, on-line games, etc.

With the rapid development of communication services, there is a very strong demand for high-bandwidth network facilities, whose capabilities are much beyond those of current high-speed networks such as asynchronous transfer mode (ATM) and SONET/SDH networks [1]-[3]. There is not enough bandwidth in our networks today to support the expected exponential growth in network traffic.

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Various physical media, such as copper wires, microwave, radio and satellite, may be used for data transmission. However, with the present technology, the data rates of these electrical media are limited to a few Giga-bits per second (Gbps) or less, and cannot match the network traffic growth that is expected. Using the principle of total internal reflection, we can transmit information in optical fibers. The use of optical fiber for communication was first proposed by Kao and Hockham in 1966 [4], [6]. In 1970, the low-attenuation optical fiber (20dB/km) was invented and, within a decade, fibers with a loss of 0.2dB/km had become available. A variety of optical networks came into existence in the late 1980s and early 1990s, which used optical fibers to replace existing copper cables in order to achieve higher transmission capacities. Potential bandwidth in a single strand of single-mode fiber is nearly 50 Tera-bits per second (Tbps), which is approximately four orders of magnitude higher than present electronic data rates of a few Gbps. Therefore, every effort should be made to tap into this huge optical bandwidth. Though optical fiber has extremely high bandwidth, only speeds (data rate) of a few Gbps can actually be achieved. This is because the rate at which an end user (such as workstation or a gateway that interfaces with lower-speed sub networks) can access the network is limited by electronic speed, which is only a few Gbps. Hence the key in designing high-capacity optical communication networks in order to exploit the fiber's huge bandwidth is to introduce concurrency among multiple user transmissions in the network architectures and protocols. In an optical communication network, this concurrency may be provided according to wavelength or frequency [wavelength-division multiplexing (WDM)], time slots [time-division multiplexing (TDM)], or wave shape [spread spectrum, code-division multiplexing (CDM)].

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All-optical TDM and CDM are still somewhat futuristic technologies. Under optical TDM, each end-user should be able to synchronize to within one time slot. The optical TDM bit rate is the aggregate rate over all TDM channels in the system, whereas the optical CDM chip rate may be much higher than each user's data rate. As a result, both optical TDM bit rate and optical CDM chip rate may be much higher than electronic processing speed, i.e., some part of an end user's network interface must operate at a rate higher than electronic speed. Thus, optical TDM and CDM are relatively less attractive than WDM, since WDM (unlike TDM or CDM) does not impose such a requirement.

Currently, WDM is the favorite multiplexing technology for optical communication networks because it supports a cost-effective method to provide concurrency among multiple transmissions in the wavelength domain [4]. Several communication channels, each carried by a different wavelength, are multiplexed into a single fiber strand at one end and demultiplexed at the other end, thereby enabling multiple simultaneous transmissions. Each communication channel (wavelength) can operate at any electronic processing speed (e.g., OC-192 or OC-768) that is currently available. For example, a fiber strand that supports 160 communication channels (i.e., 160 wavelengths, each operating at 40 Gbps) would yield an aggregate capacity of 6.4 Tbps. A future WDM optical transport network would consist of electrically controlled optical nodes. These optical nodes may be optical crossconnect (OXC) (also known as wavelength crossconnects (WXC)) [1], [5] or optical add drop multiplexers (OADMs), which perform switching of optical wavelength channels. Optical nodes can dynamically configure and reconfigure optical wavelength connections (known as optical lightpaths) between nodes so as to distribute the fiber

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route resource in the optical layer on the basis of changes in traffic demands. This would then make the best use of network resources. These optical nodes can also be used to realize protection strategies and self-healing approaches to tackle failures. These have been the major reasons behind the intense research and development efforts that we currently find in the area of WDM optical transport networks.

1.2 Motivations

As already described, the tremendous capacity of WDM optical networks offers great opportunities for new applications and services, but it also creates a new problem because any failure would now become catastrophic in nature. With a simple calculation, we can show the impact caused by a single failure. If we assume that each wavelength carrying an OC-192 channel conveys 10 Gbps, there are 16 channels in a single fiber and a modern trunk cable can accommodate up to 100 individual fibers, then the total traffic can yield 16 Tbps. If this trunk cable were to fail, 16 trillion bits would be lost every second and many millions of telephone conversations or other telecommunications services would be disrupted. WDM optical networks span globally and transmit all kinds of mundane business and personal information. Loss of communications because of failure in such a network would cause chaotic situations. Therefore, it is critically important to design WDM optical networks that are inherently fault-tolerant and protect against events such as fiber cable cuts, central office failures and hardware failures. A survivable WDM optical network provides alternate routes between a pair of nodes in case of failures. The objective of setting a level of survivability is to ensure that network performance will not degrade below a predetermined level.

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There are two main approaches for survivability: protection and restoration. In the restoration approach, the spare capacity is not reserved at the connection setup, but is only established for rerouting the disrupted traffic upon the fault's occurrence. It has a high network utilization but cannot guarantee 100% recovery, since the network may not have sufficient free capacity when the failure takes place. In the protection approach, the spare capacity is reserved during connection setup. It has a lower network utilization compared with the restoration approach but it can guarantee 100% recovery, which is crucial for WDM optical network design. Detailed discussions of restoration and protection techniques are given in Chapter 2.

In the study by Labovitz et al. [9], which analyzed Internet outage record between November 1997 and November 1998, network failures can be contributed to a variety of causes, such as power outage, maintenance upgrade, fiber cut and hardware problems. The number of occurrences due to Fiber Cut is 261, equal to 16% of the total number of occurrences. A more recent study reported by Alcatel [10] shows that the number of link failures is 20% of the total number of failures. The failure of a fiber link is the most frequent cause of network failures and may cause all lightpaths using the faulty fiber to fail. Since single fiber failure is the predominant form of failures in WDM optical networks, a lot of research has been concentrated in this area [45]-[49], [56]. The work in [45] proposed a variation of shared-path protection, called sub-path protection. The work in [46] investigates the problem of dynamic shared-path-protected lightpath provisioning in WDM optical network. In [47], the authors present a new approach for investigating the problem of routing lightpaths of a logical topology on a given physical topology so that the logical topology can withstand a physical link failure. The work in [48] and [49] decomposes a mesh topology into

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protection cycles, which then perform automatic protection switching (APS). In [54], the authors proposed a new method called pre-configured protection cycles (p -cycles), which not only inherits the fast restoration speed of protection rings but also achieves a high efficiency in the use of spare capacity. Hence it has attracted increasing attention [54]-[61]. In this thesis, we focus on protection against single fiber failure based on the method of p -cycles. Most of the works on p -cycle based protection have been concentrated on networks with static traffic, but little work has been devoted to networks with dynamic traffic demands. Therefore, there is a urgent need to study p -cycle-based dynamic network protection and restoration.

1.3 Objectives

As discussed above, provisioning 100% recovery against network failure is critically important in ultra-high capacity WDM optical networks. The main purpose of this thesis is to investigate survivable approaches for both static and dynamic WDM optical networks. The objectives are:

- (1) To investigate the issues related to WDM network survivability and analyze and compare various techniques of WDM network survivability.
- (2) To develop new efficient heuristic methods for p -cycle-based survivable network design with the aim of 100% protection but with much lower computational complexity as compared to linear integer programming approach.
- (3) To investigate the issues related to the design of survivable WDM optical networks with dynamically changing traffic demands and use the p -cycle method

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to solve the problem of dynamic protection provisioning in WDM optical networks.

- (4) To propose new approaches for WDM network survivability design so as to provide full protection with minimal spare capacity.

1.4 Main Contributions

The original contributions of this thesis are listed as follows.

- (1) To reduce the computational complexity of the integer linear programming (ILP) method, a new design heuristic, i.e., the *efficiency-ratio (ER) based unity-p-cycle* design, has been proposed for *p-cycle* based survivable WDM networks design without using the ILP. The systematic study and quantitative results on the performance of this design heuristic are also provided. Our studies show that the new heuristic performs well for both distributed and centralized traffic patterns and that in spite of its significantly lower computational time, the redundancies obtained by the new heuristic are very close to those obtained from the optimal solution.
- (2) To design survivable WDM networks supporting dynamically changing traffic demands, three strategies of extending our proposed *ER-based unity-p-cycle design* heuristic are developed and investigated. The blocking performance for these strategies has been studied under two different traffic patterns for two different test networks by computer simulation. The results have shown that Strategy-3 achieves the best blocking performance among the three strategies and its average computational time required for handling a new lightpath is comparable to that of Strategy-2. Strategy-2 is the fastest but its blocking performance is much

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worse than that of Strategy-3. Strategy-2 has a better blocking performance than Strategy-1 but it is slowest in processing new lightpaths. The simulation has also revealed that the blocking probability of Strategy-3 is the almost the same as that of the shared backup path protection (SBPP) scheme, but it has much faster restoration speed than the SBPP.

- (3) Aiming at simplifying network management and reducing processing overhead, we have considered the problem of dynamically survivable WDM networks with a *p*-cycle-base *protected working capacity envelope* (PWCE) approach. We have developed a modified new ILP model to determine the protected working capacity envelope and carried out computer simulations to evaluate the blocking performance. The simulation results have shown that the *p*-cycle-based PWCE design proposed could achieve virtually the same blocking performance as the shared path protection scheme in spite of its substantially lower computational complexity.
- (4) A new approach called shared *p*-cycles design is proposed to further improve the efficiency in the use of spare capacity for survivable WDM optical networks. We have developed an ILP formulation to solve the shared *p*-cycles design problem for both wavelength convertible and non-convertible optical networks. To compare with the conventional unshared *p*-cycles design, computer simulations have been conducted where four different test networks have been investigated. Our investigations have shown that, compared with the conventional unshared *p*-cycles design, the shared *p*-cycles design is most effective when the maximum number of spans (or nodes) allowed in the *p*-cycles is relatively small (i.e., half or less than half of the number of nodes in the network).

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1.5 Organization of the Thesis

This thesis is organized as follows. A brief introduction, which covers background, WDM optical networking, motivations and main contributions, is presented in Chapter 1. The literature review of survivability in WDM optical networks is given in Chapter 2, where different kinds of protection methods are discussed.

Chapter 3 describes a new heuristic algorithm as a sub-optimum solution for p -cycle design. Numerical studies are carried out to show that this new heuristic can perform well for different traffic patterns. The redundancy obtained by this heuristic is compared to that of the optimal solution that uses the ILP.

In Chapter 4, we extend the *ER-based unity- p -cycle design* heuristic to configure dynamic p -cycles that are adaptive to changing traffic demand in WDM networks. We consider three strategies for dynamically configuring p -cycles and compare their performance under two different traffic patterns by computer simulations.

In Chapter 5, we consider a p -cycle-based PWCE approach to design dynamically survivable WDM networks and develop a new modified ILP formulation for solving this design problem. Computer simulations have been conducted to evaluate the blocking performance.

Chapter 6 presents a newly proposed method, called shared p -cycles method for survivable WDM optical network design. An ILP model is developed to solve the shared p -cycle design problem for both wavelength convertible and non-convertible

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networks. To compare with the conventional unshared p -cycles design, we have numerically examined four different test networks. The procedure for the configuration of relevant p -cycles whenever a span fails is also presented.

Finally, in Chapter 7, the conclusion and summary of this thesis is presented. Further research areas are also discussed in this chapter.

Chapter 2 Literature Review

2.1 Introduction

Challenges presented by the exponential growth of the Internet have resulted in the intense demand for broadband services. In satisfying the increasing demand for bandwidth, WDM optical networks offer a unique opportunity because of the almost unlimited potential bandwidth that they can offer. In such high-capacity optical WDM networks, each wavelength channel has a data rate ranging from a few Gbps to 10 Gbps or higher (e.g., OC-192 or OC-768). However, a single fiber failure leads to the failure of all the lightpaths traversing the fiber and results in tremendous data loss. Therefore, effective survivability mechanisms are needed to minimize the data loss. In this chapter, we present a literature survey of survivable methods employed in high-capacity communication networks. In particular, we discuss various protection and restoration schemes reported for optical WDM networks.

It may be noted that the primary objective of network survivability is to maintain the end-to-end data service even under network resource failures such as link or node failures. In optical WDM networks, this can be achieved in different ways in different layers of the network.

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2.2 IP Layer Approach

The IP layer itself employs distributed routing algorithms [23], [30], [31], which are designed to react and adapt to topology changes that may result from resource failures. With dynamic routing, reachable active routers are found dynamically, thus adapting IP rerouting to possible network faults. This task is accomplished by exchanging, between adjacent routers, control messages that are used to update the routers' routing tables, thus enabling IP packets to be dynamically rerouted around the failed links and nodes. This protocol guarantees network-wide survivability, independent of the underlying physical network.

The routers can detect the network faults either explicitly or implicitly [32]. In the former case, faults are detected locally and signaled to the neighboring routers through customary exchange of control messages, such as Internet Control Message Protocol (ICMP) [24], whereas in the latter, the expiration of timers on background messaging, such as KEEPALIVE and HELLO messages, implicitly signals the presence of faults. Once a line fault is detected, the router reevaluates the affected routes and updates its routing tables. Subsequently, the changes are propagated to the neighboring routers using UPDATE messages such as Open Shortest Path First (OSPF), link state advertisement (LSA) [25] or Border Gateway Protocol-4 (BGP-4) [26]. The dynamic routing protocol efficiently uses spare network resources and is flexible to topological changes. However, it suffers from long reaction times and unpredictable behaviors.

Some enhancements of the protocol have been proposed [23] to overcome these drawbacks. One approach is the equal cost multipath forwarding (ECMF) [27], in

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which the router relies on more than one path for transmitting packets sharing a common destination. This solution is already implemented in some routing protocols, such as OSPF and Intermediate System-Intermediate System (IS-IS), by maintaining multiple next-hop entries for the same destination within each router's routing table. This way, in case of failure, a fraction of packets are guaranteed to flow to the destination until the router's routing table is updated with recalculated routes. A second approach partitions the network into multiple areas, as defined in hierarchical link state routing protocols such as OSPF and IS-IS. This way routing updates are confined to the affected area, minimizing the network reconfiguration convergence time. Another proposed approach decreases the failure detection time by either reducing the HELLO timeout, so HELLO messages are sent more frequently, or by rapid rate pinging through ICMP ECHO requests [33]. It may be noted that both these approaches will increase the control traffic overhead in the network.

Even though one may consider relying on the IP layer alone to restore service after a fault, this approach raises important issues that will be of some concern. One concern is the slow convergence and response time of the IP link failure detection and routing algorithms. This renders them unsuitable for use with critical or premium services. For example, IP link failure detection typically requires multiple rounds of missing hello message exchanges. Similarly, LSP failure detection can take a long time, since notification messages are propagated and processed hop-by-hop along the LSP back to the ingress router. However, these concerns may be addressed by suitable modification to the IP layer protocol behaviors.

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Another concern has to do with the scalability and efficiency of the approach. As WDM channels approach OC-192 rates (10 Gbps), there is a huge amount of traffic to be protected and rerouted in the event of a single wavelength channel (not to mention fiber) failure. Therefore instead of re-rerouting individual fine grain IP flows, it is much more scalable if a server layer protection mechanism can be engineered. The flip side of the argument of course is that the IP layer protection can be made much finer grain and therefore affords much more focused protection, without wasting unnecessary bandwidth for those flows which do not need protection.

Yet a third concern is that in a pure IP-based approach, there is no way to assure physical optical layer path diversity between the backup paths setup by an IP/MPLS protection/restoration algorithm. Obtaining such an assurance requires knowledge of the optical layer physical layout.

For carrier grade operations, it is certainly necessary to have reliable protection and restoration schemes in place. However, for many IP data applications that assume a best effort IP datagram service, it has been argued that a pure IP based recovery approach is in fact sufficient. In any case, more detailed studies are needed to decide if a pure IP-based approach can indeed compete with the optical layer protection and restoration.

2.3 MPLS Based Approach

Multiprotocol Label switching (MPLS) [28] is a switching method in which each hop by hop decision is based on a label. The ordered set of labels is called a Label

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switched Path (LSP). Each LSP has a set of criteria associated with it, which describes the traffic that traverses the LSP. A set of criteria groups the traffic into a Forwarding Equivalence Class (FEC). FECs group IP traffic together and associate with them what is commonly called a next hop: a tuple that defines the interface and the low level IP address of the next IP router. LSPs are setup using signaling protocols like Resource-Reservation Protocol (RSVP) or Constraint-based Label Distribution Protocol (CR-LDP). A switching system that can group traffic into different FECs is called a Label edge router. An LSR performs label switching by establishing a relation between an <input port, input label> tuple and an <output port, output label> tuple. Similarly, OXC provisions optical channel trail by establishing a relation between an <input port, input optical channel> tuple and an <output port, output optical channel> tuple.

Recently, MPLS-based protection and restoration schemes are being actively pursued in the IETF MPLS working group, and some research work have been done [34]-[38]. For the peering and the integrated models that adopt a unified control plane based on MPLS/GMPLS (General Multi Protocol Switch also called MP λ S) [39], it would be possible to setup alternate lambda switched paths. The routing extensions of GMPLS help scale the link state database by providing support for unnumbered links as well as hierarchical LSPs.

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Figure 2-1 A simple mesh network with working and protection path

Consider a simple mesh network shown on Fig. 2-1, each node is connected with optical routers (OXCs). Protection switching relies on rapid notification of failures. Once a failure is detected, the node that detected the failure must send out a notification of the failure by transmitting a Failure Indication Signal (FIS) to those of its upstream LSRs that were sending traffic on the working path that is affected by the failure. This notification is relayed hop-by-hop by each subsequent LSR to its upstream neighbor, until it eventually reaches a Path Switched LSR (PSL). The PSL is the LSR that originates both the working and protection paths, and the LSR that is the termination point of both the FIS and the Failure Recovery Signal (FRS). Note that the PSL need not be the origin of the working LSP. As shown in Fig. 2-1, the PSL is node 1 and node 6.

The Path Merge LSR (PML) is the LSR that terminates both the working path and its corresponding protection path. As shown in Fig. 2-1, the PML is node 8. Depending on whether or not the PML is a destination, it may either pass the traffic on to the higher layers or may merge the incoming traffic on to a single outgoing LSR. Thus,

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the PML need not be the destination of the working LSP. An LSR that is neither a PSL nor a PML is called an intermediate LSR. The intermediate LSR could be either on the working or the protection path, and could be a merging LSR (without being a PML). Since the LSPs are unidirectional entities and protection requires the notification of failures, the failure indication and the failure recovery notification both need to travel along a reverse path of the working path from the point of failure back to the PSL(s). When label merging occurs, the working paths converge to form a multipoint-to-point tree, with the PSLs as the leaves and the PML as the root. The reverse notification tree is a point-multipoint tree rooted at the PML along which the FIS and the FRS travel, and is an exact mirror image of the converged working paths.

The establishment of the protection path requires identification of the Working path, and hence the protection domain. In most cases, the working path and its corresponding protection path would be specified via administrative configuration, and would be established between the two nodes at the boundaries of the protection domain (the PSL and PML) via explicit (or source) routing using LDP, RSVP, signaling (alternatively, using manual configuration).

The advantages of the MPLS based approach are summarized as follows [40]:

- (1) It is much faster than the IP layer restoration.
- (2) It can easily provide path protection with different priorities for each path. A finer granularity of control can be established.
- (3) Features like Quality of Service can be easily brought about.
- (4) The above operations will be timer induced. So there will be no problems in the inter operation with the optical layer.

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- (5) It can incorporate a fiber level protection scheme to improve the scalability of WDM survivability schemes by using the MPLS stack function. All LSP labels are merged into a larger, fiber LSP. A full fiber LSP is switched to a similar backup LSP, which mirrors the individual LSP label assignments.
- (6) Restoring the encapsulated fiber LSP improves response times and decreases fault related MPLS signaling.

2.4 Optical Layer Approach

The optical layer can provide wavelength circuits for the routing of IP packets. Therefore it is possible to protect large amount of traffic by protecting and restoring wavelength circuits [41]. More specifically, the survivability schemes can be divided into two categories, i.e., protection and restoration schemes.

Protection schemes [14], [29] (also called proactive in [16]) pre-provide backup resources that the network can quickly utilize for recovery from a resource failure along the primary path. For example, link and node disjoint backup circuits can be setup simultaneously with the primary connection to guarantee fast switching to the protection path whenever a failure takes place. Depending on the level of recovery guarantee, the resources along the backup path may be exclusively deployed, or they may be shared among multiple backup paths, e.g., if only single-failures are to be protected, then resources can be shared among all backup paths for which their primary paths have no intersection.

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Restoration schemes [15], [29] (also called active in [16]) deploy backup resources dynamically only at the time when failures occur. Recovery is done by appropriate signaling triggered by the detection of failure. This has the advantage that overheads are low in the absence of failures. However, it does not guarantee successful recovery. Many schemes exist for doing this which provide both end-to-end and hop-by-hop recovery, along with possible preemptive and nonpreemptive variants [15], [19]-[22], [29].

Because of their simplicity, protection schemes are typically fast and are most popular in traditional SONET/SDH rings [1], [17]. Restoration schemes are much more complex and slower, and do not guarantee successful recovery. However they are more flexible and adaptive, and may be amenable to a distributed on-line implementation [19]. These protection and restoration schemes can be divided into path-based protection/restoration and link-based protection/restoration. Fig. 2-2 illustrates the classification of survivability approaches that may be employed in the optical layer.

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Figure 2-2 Survivability methods in optical layer [16]

2.4.1 Link-Based Method

In the link protection/restoration approach, all the lightpaths that traverse the failed link are rerouted around that link as shown in Fig. 2-3. The source and destination nodes of the lightpaths traversing the failed link are oblivious to the link failure. For link-based protection, during the primary lightpath setup, a backup path and spare wavelength are reserved around each link of the primary lightpath. For link restoration, the end-nodes of the failed link dynamically choose a route around the link, and assign a spare wavelength to this backup route. For an example shown in Fig. 2-3, the primary lightpath for node 1 to node 6 is 1-2-5-6. If the link 2-5 fails, the end nodes 2 and 5 of this failed link discover another route 2-3-4-5, so the backup lightpath is 1-2-3-4-5-6. It may be noted that the end nodes of the primary lightpath 1 and 6 do nothing to handle this link failure.

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Figure 2-3 Link-based method

Dedicated Link-Based Protection: For dedicated path-based protection, for each link of the primary path, a backup path as well as a spare wavelength are reserved around that link and are dedicated to that lightpath, at the time when a lightpath is set up.

Shared Link-Based Protection: In shared link-based protection, a backup path as well as a spare wavelength is reserved around each link of the primary lightpath, at the time when a lightpath set up. The difference between this and dedicated link-based protection is that the backup wavelengths reserved on the links of the backup lightpath can be shared with other backup lightpaths. As a result, backup wavelength channels are multiplexed among different failure scenarios (which are not expected to occur simultaneously), and therefore shared link-based protection is more capacity-efficient when compared to dedicated link-based protection.

Link-Based Restoration: In link-based restoration, the end nodes of the failed link participate in a distributed algorithm to dynamically select a lightpath around the link.

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If no new lightpath is discovered for the failed lightpath, the connection of this lightpath is blocked.

2.4.2 Path-Based Method

In path-based protection/restoration scheme as illustrated in Fig. 2-4, when a link fails, the source node and the destination node of each connection that traverse the failed link are informed of the failure. It is the end nodes of the affected lightpaths, not the end nodes of the failed link, which perform the protection switching. For the simple example shown in Fig. 2-4, the primary path is 1-2-5-6. If the link 2-5 fails, the end nodes of this primary lightpath will choose another lightpath 1-3-4-6.

Figure 2-4 Path based method

Dedicated Path-Based Protection: In dedicated-path protection (also called 1+1 protection), the resources along a backup path are dedicated to only one primary lightpath and are not shared with the backup path for other primary lightpaths.

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Shared Path-Based Protection: In shared-path protection, at the time of a lightpath setup, a backup path and also a spare wavelength are reserved. The difference between this and dedicated path-based protection is that the backup wavelengths reserved on the links of the backup lightpath can be shared with other backup lightpaths. As a result, backup wavelength channels are multiplexed among different failure scenarios (which are not expected to occur simultaneously), and therefore shared-path protection is more capacity-efficient when compared to dedicated-path protection.

As illustrated in Fig. 2-2, dedicated (or shared) path-based protection schemes can be further classified into failure dependent and independent schemes. With the failure dependent scheme, a backup lightpath can use any link, including those used by the failed primary lightpath (working links), except the failed link. With the failure independent scheme, a backup lightpath has to be link-disjoint with the primary lightpath, that is, the backup lightpath should not have any fiber-links in common with the primary lightpath.

As an example shown in Fig. 2-5, suppose that the primary path is 4-5-6-7. If link 5-6 fails, with the failure independent approach, we cannot choose link 4-5 and 6-7 for the backup lightpath, so the backup lightpath is selected as 4-1-2-3-7; with the failure dependent approach, we can choose link 4-5 and 6-7 for the backup lightpath, so the backup lightpath can be either 4-5-2-3-7 or 4-1-2-3-6-7.

Path Restoration: In the path restoration approach, the end nodes of the failed lightpath participate in a distributed algorithm to dynamically select a lightpath. If no

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new lightpath is discovered for a failed lightpath, the connection of this lightpath is blocked.

Figure 2-5 The difference of failure independent and failure dependent

Research on survivability in the optical layer has attracted considerable attention in recent years. Some of the issues have been addressed in literature. In [41] and [42], 1+1 protection and other WDM network architectures with optical protection are examined. The work in [14]-[16], [29] compares different survivable techniques. The work in [43] presents efficient routing algorithms for computing the primary and backup routes in an optical network. In [44], the authors present connection management algorithms for a survivable WDM optical network. A variation of shared-path protection, called sub-path protection is introduced in [45].

2.5 *p*-Cycle-Based Protection Method

There are three well-known protection techniques, namely ring, mesh and pre-configured protection cycles (*p*-cycles), for optical networks. Among them, the *p*-cycles based technique has attracted increasing attention [54]-[61]. The ring based

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protection method was originally developed for SONET/SDH bi-directional line-switched rings [17]. It uses a simple mechanism whereby only two nodes adjacent to the failed link or node need to perform automatic protection switching, and hence is very fast (typically within 50 ms for SONET/SDH rings). However, the ring-based protection is not efficient when it is directly applied to optical mesh networks where many protect rings (or cycles) [48]- [52] may be formed to protect all working wavelengths in the network, since a protection ring only protects working wavelengths on the ring itself. As a result, the ratio of total spare to working capacity (known as redundancy) is at least 100% and may go up to 200% [50].

Figure 2-6 Protection in a BLSR

Fig. 2-6 shows how protection is performed in a bi-directional line switched ring (BLSR) [17]. As illustrated in Fig. 2-6, if span 1-2 fails, the switch in nodes 1 and 2 will take action. Upon the failure of span 1-2, the traffic from node 1 to node 2 will be transmitted via 1-4-3-2 using the inner ring and the traffic from node 2 to node 1 will be transmitted via 2-3-4-1 using the outer ring.

In mesh networks, there are several methods of finding rings to achieve 100% protection. In [48], the authors present the approach of oriented cycle double covers,

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which decomposes a mesh network into several elementary cycles such that each edge is present in at least one cycle. Then, it uses ring function to realize protection. Another method called “generalized loopback” was reported in [49]. An approach for economically optimized co-design of ring and mesh network components in a single hybrid transport network is described in [51]. In [52], the authors present the strategy of ring mining, which is based on logical “disassembly” and reuse of ring transmission spans to form a new mesh (or hybrid) target architecture. All these approaches enable design solutions having exactly one working and one-protection fibers on every span, so that the redundancy is at least 100%.

The p -cycles method proposed by Grover in [54] not only inherits the fast restoration speed of protection rings but also achieves a high efficiency in the use of spare capacity. This is because the p -cycles method makes use of the basic ring protection mechanism, but it goes beyond the functionality of rings. Unlike rings, p -cycles can protect not only on-cycle spans but also straddling spans [54]-[57]. A straddling span is an off-cycle span having p -cycle nodes as endpoints. Fig. 2-7 shows an example of using a p -cycle (1-2-3-5-1) for protection of both on-cycle and straddling spans. In Fig. 2-7 (b), the span 1-2 on the cycle breaks and the surviving arc of the p -cycle is used to provide protection. In Fig. 2-6 (c-d), the same p -cycle is used to protect the failure of a straddling span 1-3. As illustrated in Fig. 2-7, a bidirectional p -cycle can provide one backup path for any on-cycle span and two backup paths for any straddling span.

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Figure 2-7 An example of the p -cycle method (a) a simple p -cycle (b) a on-cycle span fails
 (c)-(d) a straddling span fails

From Fig. 2-7, we can clearly see that a bidirectional cycle in a mesh network can provide one backup path for any span on cycle and two backup paths for any straddling span. If the topology of a network is fully connected, a cycle can provide protection for N (N is the number of nodes on cycle) on-cycle spans and $\binom{N}{2} - N$ straddling spans. The cycle is formed in the spare capacity of the network. Therefore, if the spare capacity in each span of the cycle is 1, it can provide 1 working capacity in every on-cycle span and 2 working capacity in each straddling span. Therefore, the total working capacity that can be protected by the cycle is

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$2 \times \left(\binom{N}{2} - N \right) + N = N(N-2)$. Since the total spare capacity is N , this implies that the redundancy is $1/(N-2)$ for $(N \geq 3)$. Using directional cycles, we can get the same result [60]. It has been proved in [56] that p -cycles have the same lower bound on the redundancy as a span restorable mesh network, namely the well-known lower limit of $1/(\bar{d}-1)$ where $\bar{d}$ is the average span degree of nodes [62], [63].

In recent literatures, a lot of works have been reported in solving the p -cycles design problem. Reference [55] describes a distributed autonomous protocol through which a network can self-organize a near optimum set of p -cycles within itself, as an interesting alternative to centralized control of p -cycles configuration (which of course remains an option). Reference [56] is a more theoretical analysis substantiating the prior experimental findings of such high capacity efficiency and also proving that p -cycles are as efficient as any class of preconfigured spare capacity structure that can exist for restoration. In [57], the authors extend the concept of p -cycles to the IP layer and discuss their application in the context of node failure. Comparisons of the p -cycles method and other methods (ring-mining, enhanced rings and ring-mesh hybrids et al.) are given in [58], [59]. An integer linear programming (ILP) model for optimal p -cycles design with or without wavelength conversion is reported in [60]. A detailed description on ILP (including a simple example of ILP model) is given in Appendix I. In [60], an ILP model is developed for joint optimization of working and spare capacity.

Chapter 3 A Heuristic Algorithm for *P*-Cycle Design

3.1 Introduction

Fast protection and restoration against network component failures will be critically important in future optical WDM networks, since a network component failure may lead to severe disruptions in communication services [14], [16]. There have been basically two approaches to design of survivable WDM networks, namely ring and mesh. The ring protection method uses a simple mechanism where only the two nodes adjacent to the failure link or node need to perform protection switching. It is therefore very fast (typically within 50 ms), but it is also relatively inefficient as the ratio of reserved spare to working capacity (known as redundancy) is at least 100% [50], [64]. The mesh protection method can achieve a much better efficiency in the use of spare capacity, but requires a much longer restoration time due to a complicated signaling process [64]-[66].

The method of pre-configured protection cycles, known as *p*-cycles, proposed by Grover [54], can achieve ring-like fast speed with mesh-like high efficiency in the use

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of spare capacity. This is because the p -cycles method makes use of the basic ring protection mechanism, but it goes beyond the functionality of rings. The p -cycle design problem has been intensively studied and formulated as ILP, which is very computationally intensive if the number of network nodes is large. In this chapter, a new heuristic algorithm is proposed as a sub-optimum solution for fast on-line protection. Numerical studies show that this new heuristic performs well for different traffic patterns. The redundancy obtained by this heuristic is very close to that of the optimal solution but with much reduced computational time.

3.2 AE and TS Based Heuristic for p -Cycle Design

The design of a min-cost set of p -cycles to protect a given set of working flows is an NP hard problem [66], [67]. The basic formulation generates large problem files that can be difficult to solve to optimality, primarily because of the size of the set of candidate cycles to consider. To reduce the computational complexity, a method of pre-selecting a reduced number of candidate p -cycles was proposed in [61], where two pre-selection metrics, namely topological score (TS) and apriori efficiency (AE) of p -cycles, were reported to pre-select p -cycles; subsequently, the ILP was applied to these pre-selected p -cycles to solve the p -cycle design problem.

To reduce the number of candidate p -cycles, two pre-selection metrics are considered based on insights about what makes for the most efficient p -cycles in the context of a given network design. The *topological score* (TS) and the *apriori efficiency* (AE) of a cycle j are defined as in (4-1) and (4-2), respectively, where S is the set of spans, $x_{ij}=1$

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if span i is part of cycle j , $x_{ij} = 2$ if span i straddles cycle j and $x_{ij} = 0$ otherwise. C_i is the cost or distance of span i .

$$TS(j) = \sum_{i \in S} x_{ij} \quad (3-1)$$

$$AE(j) = \frac{TS(j)}{\sum_{(i \in S | x_{ij}=1)} C_i} \quad (3-2)$$

Whereas the basic solution model requires representation of all distinct cycles (possibly up to a circumference limit), the set of all distinct cycles are ranked simply by either TS or AE measures [63], and only a limited number of the top-ranked candidates are considered for representation in the ILP model. The pre-selection of p -cycles substantially reduces the computational complexity in using ILP to solve the design problem.

3.3 New Heuristic Algorithm for p -Cycle Design

Our study has found that the pre-selection method may not perform well for certain traffic pattern. In this chapter, we consider an attractively simple heuristic to solve the p -cycle design problem without using ILP. It is obvious that many complex problems can be decomposed into easier sub problems. It is possible that a sub problem may not have an optimal solution while the former may have one. Moreover, even if all the sub problems have optimal solutions, combining them may not give the globally optimal solution. However, the decomposition approach is still helpful to reduce the complexity and also to illustrate the computation procedure. We follow this idea, and propose a heuristic algorithm to achieve a sub-optimum solution for p -cycle design.

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In the following discussion, this heuristic algorithm is called *Efficiency ratio (ER)-based unity- p -cycle design* [68], [69]. The heuristic itself appears to have been independently developed by both ourselves in [68] and [69], and by W. Grover in [70] and [71] and has also been called the capacitated iterative design algorithm (CIDA) in [71]. The CIDA algorithm deals with networks where, between a given node pair, the traffic demands in both directions are assumed to be identical (i.e., the traffic demand from node i to node j is equal to that from node j to node i), and hence bi-directional cycles (with equal capacities in both clockwise and counter clockwise directions) are considered. In general, network traffic is unlikely to be symmetric in both directions between two nodes. This means that the number of working and protection wavelengths is not likely to be the same in both directions. The case of bidirectional lightpaths is a specific case of unidirectional lightpaths, since a bidirectional lightpath can always be considered as a set of two unidirectional lightpaths operating in opposite directions. Therefore, as in [60], we consider unidirectional lightpaths, and unidirectional p -cycles for protection provisioning. Our *(ER)-based unity- p -cycle design* is more generic as compared with Grove's bidirectional p -cycle heuristic design, since our heuristic can deal with both bidirectional and unidirectional traffic demands whereas Grove's heuristic can only handle bidirectional traffic demands.

We define one unit of capacity as one wavelength on each directional span throughout this chapter. We use *unity- p -cycle* to denote a unidirectional p -cycle whose capacity on every span is one unit of wavelength. A unity- p -cycle can protect one working unit in the opposite direction for every on-cycle span, and two working units (one in each direction) for every straddling span. The number of spare units of a unity- p -cycle is equal to the number of spans on the cycle. We define the ER of a unity- p -cycle as the

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ratio of the number of working units that are actually protected by the unity- p -cycle to the number of spare units of the unity- p -cycle:

$$ER(j) = \frac{\sum_{(i \in E | w_i' \geq 1)} x_{i,j}}{\sum_{(i \in E)} p_{i,j}} \quad (3-3)$$

Where E is the set of uni-directional edges. w_i' is the number of unprotected working units on edge i at present time. $p_{i,j}$ indicates if edge j is an element of p -cycle i or not; $p_{i,j}=1$ if edge j is an element of p -cycle i , otherwise $p_{i,j}=0$. $x_{i,j}$ indicates if the working units on edge j can be protected by p -cycle i or not; $x_{i,j}=1$ if the working units on edge j can be protected by p -cycle i , otherwise $x_{i,j}=0$.

Note that the ER of a unity- p -cycle is determined by both the topology and the working units that are actually protected by the unity- p -cycle, and hence it represents the posteriori efficiency of the unity- p -cycle, whereas the pre-selection metrics of TS and AE of a p -cycle are decided by the topology only [61]. A unity- p -cycle with a greater ER means that its spare units are utilized more efficiently than a unity- p -cycle with a smaller ER. The idea behind this heuristic is to identify those unity- p -cycles that can actually protect as many working units as possible, and hence to reduce the total spare units.

Our algorithm is used for SCA (spare capacity assignment) and the target is to use minimal spare capacity to provide 100% protection. In this problem, the total working capacity is given, so the target is to minimize the redundancy. The method of p -cycles is to use different cycles to achieve full protection. For a given network topology, the number of cycles which can satisfy the constraints (2-2)-(2-5) will be large when the

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number of nodes in the network is large. ILP method will enumerate all sets of cycle selection, and then choose the one with minimal total spare units. Hence ILP method is very computational intensive. If the number of working units of each unidirectional edge is given, the set of p -cycle with minimal total spare capacity is equal to the set of p -cycle with minimal redundancy. The redundancy is the ratio of total number of spare

units to total number of working units: $\text{Redundancy} = \frac{\sum_{(i \in E)} s_i}{\sum_{(i \in E)} w_i}$, where s_j and w_j are

the number of spare and working units required on edge j , respectively.

For a given network topology and traffic demand, we first find all candidate cycles according to the algorithm in [72] and determine the working capacity on each span based on certain shortest-path routing algorithm [60]. Then we calculate the ER of unit- p -cycle of each candidate cycle and select a unity- p -cycle with the maximum ER. Finally, by subtracting the working units of each unidirectional edge which can be protected by the selected unity- p -cycle, we update the number of working units on each unidirectional edge. We then repeat the process until there remains no unprotected working units on any unidirectional edge.

The pseudo-code for the ER-based heuristic design is as follows:

```

ER- based unity- $p$ -cycle design() {
  Initialize CycleSet, work[], and CycleUse[]
  CycleSet = FindCycles()
  While work[i] > 0 for each unidirectional eage  $i$  {
    Max_Cycle = 0
    For each cycle  $p$  in CycleSet {
      Calculate ER( $p$ );
      If ER( $p$ ) > ER(Max_Cycle) {
        Max_Cycle= $p$ ;
      }
    }
  }
  CycleUse[Max_Cycle]= CycleUse[Max_Cycle]+1;
}

```

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```
For each unidirectional edge  $j$ , if  $\text{work}[j]>0$  and  $x_{\text{max\_cycle},j}>0$ 
{
     $\text{work}[j]=\text{work}[j]-1$ ;
}
}
Return(CycleUse)
}
```

In the above pseudo-code, the *FindCycles()* function is used to find a set of candidate cycles.

The flowchart of the algorithm is shown in Fig. 3-1.

Figure 3-1 The flowchart of the *ER*-based unity-*p*-cycle design heuristic algorithm

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Figure 3-2 A simple network showing three cycles and working capacity

Table 3-1 The ER for all the unity-*p*-cycles in Fig. 3-2 (a)

Cycle Number	Efficiency ratio (ER) of unity- <i>p</i> -cycle	
	Clockwise	Counter-clockwise
1	1.00	0.75
2	1.33	1.17
3	1.00	1.00

We use the simple network in Fig. 3-2 to show how the algorithm works. Here the numbers on the spans indicate the working units and the notation “span $i \rightarrow j$ ” denotes a directional span from node i to node j . Fig. 3-2(a) illustrates the initial working units on each span. There are three candidate cycles, each of which can be in either the clockwise or counter-clock direction. Since cycle 2 has 6 spans, its unity-*p*-cycle in the clockwise direction requires 6 spare units and can protect 8 working units (including 1 unit on each of the two straddling spans $5 \rightarrow 2$ and $2 \rightarrow 5$, and 1 unit on each of the six on-cycle spans $1 \rightarrow 4$, $4 \rightarrow 5$, $5 \rightarrow 6$, $6 \rightarrow 3$, $3 \rightarrow 2$, $2 \rightarrow 1$), and hence its current ER is $8/6=1.33$. But its unity-*p*-cycle in the counter-clockwise direction can only protect 7 working, because the working units on span $5 \rightarrow 4$ is 0, its current ER is $7/6=1.17$. The current ERs for all the unity-*p*-cycles in Fig. 3-2 (a) are given in Table

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3-1. As the clockwise unity-*p*-cycle of cycle 2 has the maximum ER, it will be selected and the working units that can be protected by this unity-*p*-cycle will be removed. The remaining working units on each span are shown in Fig. 3-2(b).

3.4 Finding Cycles

The first step in our algorithm is to find all the simple cycles. A simple cycle is a cycle whose nodes are pair-wise different, which was originally defined in [60]. Here we use the algorithm called edge-digraph [72] to realize the *FindCycles()* function in the pseudo-code described in the previous section. A network is modeled as graph $G(V, E)$ with V as the set of nodes and E as the set of bi-directed edges. We denote e as an arbitrary edge in E , i.e., $e \in E$. The details of the algorithm are shown in the following:

1. Find any edge $e \in E$, delete e from G ;
2. Find a set of all the paths P_e between the two nodes of e in G ,

$$P_e = \{P_e^1, P_e^2, \dots, P_e^k\};$$

3. A set of candidate backup cycles are obtained by joining e with P_e , i.e.,

$$e \cup P_e = \{e, P_e^1, P_e^2, \dots, P_e^k\};$$

4. Go to step 1 until there are only two edges in G .

We next modify the algorithm of the *k*-shortest path reported in [73], which is used to find all the paths with a limited length. The length of a path is defined as the summation of the length of each link along the path. We say that a path has a limited

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length if its length does not exceed a pre-determined value. For an example, if the value is 100 km, the length of the candidate path cannot exceed 100 km. If we set the limited length to infinity, we can find all the possible paths between two nodes. If we just use the paths with a limited length in step 2, we can find all the cycles whose length do not exceed the pre-determined value. If there are N paths $P_1, P_2, \dots, P_N$ between two nodes, the length of each path is $L_1, L_2, \dots, L_N$ and $L_1 \leq L_2 \leq \dots \leq L_N$, the k th shortest path is P_k .

The algorithm of finding all the paths between two nodes and some notations and definitions are given below:

Let N be the number of nodes in the network, node 1 be the origin and node N is the sink;

(1)-(i)- $\dots$ -(j), $i \neq j \neq \dots \neq 1$, be the path from (1) to (j), passing through (i), $\dots$ ($j-1$);

$d_{ij} \geq 0, i \neq j$, be the distance of the direct link from (i) to (j), if this link exists, d_{ij} is a finite number, otherwise, d_{ij} is considered to be infinity;

$A^k = (1) - (2^k) - (3^k) - \dots - (Q_k^k) - (N)$, $k = 1, 2, 3, \dots$, be the k th shortest path from (1) to (N), where $(2^k), (3^k), (Q_k^k)$ are respectively the 2nd, 3rd, $\dots, Q_k$ th node of the k th shortest path;

$A_i^k, i = 1, 2, \dots, Q_k$, be a set of “deviations from A^{k-1} at (i)” – a “deviation from A^{k-1} at (i)” is the shortest of the paths that coincide with A^{k-1} from (1) to the i th node on the path and then deviate to a node that is different from any the $(i+1)$ st nodes of those $A^j, j = 1, 2, \dots, k-1$, that have the same paths from (1) to the i th node as does

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A^{k-1} (for an example, if path A^j has the same paths for (1) to the i th node as does A^{k-1} , the $(i+1)$ st node of A_i^k must be different from the $(i+1)$ st node of A^j , $1 \leq j \leq k-1$); and finally reaches (N) by a shortest subpath without passing any node that is already included in the first part of the path (from (1) to i th node). Note that the A^k is loopless and contains the same node no more than once.

R_i^k be the root of A_i^k - the root of A_i^k is the subpath of A_i^k that coincides with A^{k-1} , i.e., $(1)-(2^k)-\dots-(i^k)$ in A_i^k ; S_i^k be the spur of A_i^k -the spur of A_i^k is the last part of A_i^k that has only one node coinciding with A^{k-1} , i.e., $(i^k)-\dots-(N)$ in A_i^k .

1. Using Dijkstra's algorithm [74] to find the shortest path named A^1 between the two nodes, $k=1$;
2. If the path length is longer than the limited length L , we are done, otherwise $k=k+1$ and go to step 3;
3. For each of $i=1,2,3,\dots,Q_{k-1}$, do the following:
 - (a) Check if the subpath consisting of the first i nodes of A^{k-1} in sequence coincide with the subpath consisting of the first i of A^j in sequence for $j=1,2,\dots,k-1$. If so, set $d_{iq} = \infty$ -where (q) is the $(i+1)$ st node of A^j ; otherwise, make no changes. Then go to step (b). Note that d_{iq} 's are set to ∞ for computations in iteration k only. They should be replaced by their original values before iteration $k+1$ starts.
 - (b) Apply Dijkstra's algorithm to find the shortest path from (i) to (N) , allowing it pass through those nodes that are not yet included in the path. Note that the subpath from (1) to (i) is R_i^k , the root of A_i^k ; and the subpath from (i) to (N) is S_i^k , the spur of A_i^k . Find A_i^k by joining

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R_i^k and S_i^k . Then add A_i^k to list B. We have set $d_{iq} = \infty$, hence the new path A_i^k is different from A^j , $j = 1, 2, \dots, k-1$.

4. If list B is empty, we are done, otherwise find from list B the path that has the minimum length, and go to step2.

Note that A^k is a deviation from A^j , $j = 1, 2, \dots, k-1$. More precisely, A^k must coincide with A^j , $j = 1, 2, \dots, k-1$, for the first $m \geq 1$ node(s) then deviates to a different node and finally arrives at the sink without passing each node more than once. Therefore to obtain A^k , it is only necessary to look for all shortest deviations from A^j 's, then scan from these deviations the one that has the shortest length.

3.5 Numerical Results

To examine the effectiveness of this design heuristic, we have chosen the pan-European COST 239 network [75], [76] and three other networks reported in [64] as the test cases. The topologies of these four test networks are shown in Fig. 3-3. We assume that each node performs full wavelength conversion, i.e., a lightpath can be switched to an output fiber at any free wavelength, each span has two fibers for bi-directional transmission, and the number of wavelengths per fiber is 64. Note that a network without wavelength conversion can be considered as a set of parallel networks each with a different wavelength, and hence the heuristic algorithm can be applied to each of the parallel networks. We consider two different traffic patterns, which represent two extreme situations (other situations lie in between these two situations):

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- (i) Distributed pattern: the number of lightpaths between any two nodes is selected from 1 to 10 (both inclusive) using a uniform random distribution:

$$\begin{cases} Demand(i, j) = Random(), i \neq j \\ Demand(i, j) = 0, i = j \end{cases}$$

$Demand(i, j)$ represents the number of the lightpaths requested from node i to node j .

$Random()$ is the function to produce random number uniformly distributed between 1 and 10 (both inclusive).

- (ii) Centralized pattern: each node has lightpath demands from and to a central node only and the number of lightpaths between the central node and any other node is a uniformly-distributed random integer between 1 and 10 (both inclusive). In our simulation, we choose node 1 as the central node.

$$\begin{cases} Demand(1, j) = Random(), j \neq 1 \\ Demand(i, 1) = Random(), i \neq 1 \\ Demand(i, j) = 0, otherwise \end{cases}$$

The lightpath requests are routed based on Dijkstra's algorithm [74], and the metric for each unidirectional edge is reciprocal to the free capacity of the span [60]. For an example, at initial, each unidirectional edge has 64 wavelengths; hence each edge has the same metric of 1/64. The details of routing algorithm are shown in follows:

- 1) First, assign free capacity to each span. In our simulation, it is assumed that each span has two bi-directional optical fibers, up to 64 wavelengths is allowed per fiber. So each unidirectional span has 64 units of free capacity. Next, a matrix b is created with elements reciprocal to the free spare capacity of the spans. i.e. if link exists between node i and j , $b[i][j] = 1/64$, otherwise $b[i][j] = \infty$, in the program we use a large number to substitute ∞ .

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- 2) Start from node pair 1 and 2, if there are demands from node 1 to node 2, substitute b matrix into Dijkstra's algorithm, and find out the shortest path between each two nodes.
- 3) Along the shortest path, if the shortest distance is a finite number, assign one working capacity on each link ($work(i, j) = work(i, j) + 1$), and at the same time, reduce the corresponding free spare capacity by 1. The elements in b are updated as $1 / (\text{new spare capacity})$ respectively.
- 4) The steps are repeated until all the demands are routed in the network.

Figure 3-3 The topologies of four test networks

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An example of the demand matrix of COST239 network is given below:

	1	2	3	4	5	6	7	8	9	10	11
1	0	5	3	9	5	2	9	5	2	7	1
2	3	0	8	4	2	4	2	5	5	2	2
3	4	3	0	4	1	2	2	2	0	8	3
4	3	2	2	0	3	2	6	8	2	1	4
5	4	1	5	5	0	4	4	9	5	2	1
Demand = 6	5	3	4	5	5	0	3	6	3	9	3
7	0	7	3	3	4	3	0	5	7	3	7
8	6	1	3	6	2	2	10	0	10	5	3
9	3	1	3	3	4	5	5	2	0	3	5
10	8	3	3	5	5	4	7	8	3	0	2
11	1	4	2	7	3	6	7	4	3	7	0

Here demand(i, j) is the number of lightpath requests from node i to node j , total demands is the total lightpath requests in the network, in this example it is

$$\sum_{i=1}^{11} \sum_{j=1}^{11} \text{demand}(i, j) = 450.$$

Using the routing algorithm, we can get the working capacity in each link:

	1	2	3	4	5	6	7	8	9	10	11
1	0	19	0	19	0	0	0	18	0	0	18
2	15	0	18	18	0	0	19	0	0	0	15
3	0	14	0	13	13	0	18	0	0	17	0
4	17	10	12	0	11	0	0	0	0	0	0
5	0	0	18	18	0	18	0	0	0	18	12
Work = 6	0	0	0	0	18	0	19	18	18	18	0
7	0	17	16	0	0	12	0	18	0	0	16
8	15	0	0	0	0	16	19	0	19	0	16
9	0	0	0	0	0	16	0	18	0	17	16
10	0	0	18	0	18	17	0	0	18	0	0
11	16	18	0	0	18	0	18	18	18	0	0

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The work(*i, j*) is the number of working wavelength channels in link (*i, j*).

work(*i, j*)=0 represents there is no edge between node *i* and node *j*. In this example,

the total number of working wavelength channels is $\sum_{i=1}^{11} \sum_{j=1}^{11} \text{work}(i, j) = 867$.

Table 3-2 Difference of Redundancy for COST239 networks

Maximum allowed cycle length	Distributed traffic pattern					
	ER-based unity- <i>p</i> - cycle		Pre-selection (TS)		Pre-selection (AE)	
	Diff	95% CI	Diff	95% CI	Diff	95% CI
3500	0.0302	0.020 ~ 0.05	0.028	0.022 ~ 0.034	0.0100	0.008 ~ 0.012
4500	0.0321	0.026 ~ 0.041	0.0200	0.015 ~ 0.024	0.009	0.005 ~ 0.014
5000	0.0477	0.034 ~ 0.052	0.0250	0.016 ~ 0.033	0.008	0.006 ~ 0.010
5500	0.0272	0.022 ~ 0.032	0.0150	0.010 ~ 0.019	0.006	0.004 ~ 0.010
6000	0.0114	0.08 ~ 0.015	0.0100	0.07 ~ 0.012	0.005	0.004 ~ 0.008
6500	0.0141	0.009 ~ 0.019	0.0100	0.006 ~ 0.011	0.006	0.004 ~ 0.009
Infinity	0.0130	0.010 ~ 0.016	0.01	0.007 ~ 0.013	0.005	0.002 ~ 0.08
Maximum allowed cycle length	Centralized traffic pattern					
	ER-based unity- <i>p</i> - cycle		Pre-selection (TS)		Pre-selection (AE)	
	Diff	95% CI	Diff	95% CI	Diff	95% CI
3500	0.0445	0.022 ~ 0.067	0.1566	0.122 ~ 0.183	0.142	0.112 ~ 0.173
4500	0.048	0.036 ~ 0.058	0.146	0.113 ~ 0.180	0.128	0.091 ~ 0.162
5000	0.0552	0.042 ~ 0.069	0.152	0.102 ~ 0.206	0.137	0.100 ~ 0.261
5500	0.0480	0.035 ~ 0.062	0.142	0.110 ~ 0.181	0.134	0.102 ~ 0.163
6000	0.0267	0.020 ~ 0.035	0.126	0.008 ~ 0.172	0.106	0.006 ~ 0.142
6500	0.0196	0.011 ~ 0.029	0.108	0.061 ~ 0.145	0.094	0.038 ~ 0.140
Infinity	0.0231	0.012 ~ 0.35	0.086	0.0042 ~ 0.125	0.067	0.003 ~ 0.102

Fig. 3-4 compares the average redundancy obtained by the *ER-based unity-*p*-cycle design*, the pre-selection method (500 cycles were pre-selected based on the AE and

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TS metrics) and the optimal solution using the ILP for the COST 239 network under both traffic patterns (based on all simple cycles) versus maximum allowed cycle length. For each test case, we generate 10^3 lightpath requests matrices. Here we firstly calculate the total working capacity of each demand matrix and then use the ILP, pre-selection method and our *ER-based unity-p-cycle design* to calculate the total spare capacity respectively. Our most interesting is how far the redundancy achieved by each heuristic from the redundancy achieved by optimal solution using ILP. Table 3-2 compares the difference of redundancy between each heuristic method and the optimal solution using ILP. 95% CI is the 95% confidence interval for the redundancy difference (Diff) between the optimal solution and a heuristic method. A confidence interval is a range of values that has a specified probability of containing the parameter being estimated [77]. The 95% confidence interval, which has a probability of 0.95 to contain the parameter, is most commonly used to ensure that the estimated data obtained from simulation has reasonable accuracy. The results are summarized as follows:

- (1) The *ER-based unity-p-cycle design* works well for both traffic patterns. The redundancy obtained by the *ER-based unity-p-cycle design* is very close to that of the optimal solution with a difference less than 5% for various max. allowed cycle lengths.
- (2) The pre-selection method is slightly better than the *ER-based unity-p-cycle design* for the distributed traffic pattern. However, it does not perform well for the centralized traffic pattern. Its redundancy is about 15% higher than that of the optimal solution, and about 10% higher than that of the *ER-based unity-p-cycle design* when the limited cycle length is 3500km.

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- (3) The redundancy is significantly reduced as the max. allowed cycle length increases for all the methods.

Figure 3-4 Redundancy comparison among different methods for the COST239 network

Fig. 3-5 shows the computational time versus the max. allowed cycle length for the COST 239 network for both traffic patterns. For pre-selection methods and optimal solution using ILP, the computational time can be calculated by the software CPLEX (see details in Section 2.7, the solution time). In our simulation, we use C language to realize our *ER-based unity-p-cycle design* and use function clock () to calculate computational time. The computational time is only the time for the selection of p -cycle, and the time for cycle search and lightpath demand routing are not included in.

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Figure 3-5 omputational comparison time among different methods for the COST239 network

Note that the computing platform used is Intel Pentium IV 2.4GHz PC running Windows 2000 with 512 MB memory and 40GB hard disk. The results in Figure 3-5 can be explained as follows. As the maximum allowed *p*-cycle length increases, the number of candidate cycles is increased substantially. For an example, the number of candidate cycles grows from 1000 to 7000 when the maximum allowed *p*-cycle length is increased from 3500 km to infinity. As the number of candidate cycles increases, the number of variables in the ILP model is substantially increased and hence the computational time for the optimal solution using ILP increases dramatically from 1.9 to 55 seconds for the distributed traffic pattern. For the ER-based unity-*p*-cycle design, the computational time is much lower, increasing from 0.015 to 0.15 seconds, since the ILP is not required. For the pre-selection method, the number of pre-selected candidate *p*-cycles is always fixed at 500 and hence the computational time is constant at 0.85 seconds for the distributed traffic pattern. Similar results for the centralized

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traffic pattern are also shown in Fig. 3-5. Therefore, we can conclude that with the computational time is that low, our *ER-based unity-p-cycle design* could easily be implemented in a real network, and executed in a dynamic fashion, each time the network state changes.

Table 3-3 Redundancy comparisons for different networks

Test Network			Test Network2	Test Network 3	Test Network 4
Number of nodes			11	15	19
Number of edges			40	56	78
Average node degree			3.6364	3.733	4.1053
Number of all Cycles			304	1952	28412
Number of pre-selection cycles			100	600	9000
Redundancy	Distributed pattern	Optimal (ILP)	64.7%	52.8%	41.8%
		ER-based unity- <i>p</i> -cycle	72.5%	60.6%	47.1%
		Pre-selection (TS)	71.2%	59.5%	45.8%
		Pre-selection (AE)	68.4%	55.2%	43.2%
	Centralized pattern	Optimal(ILP)	68.5%	56.5%	45.4%
		ER-based unity- <i>p</i> -cycle	72.5%	60.2%	49.6%
		Pre-selection (TS)	83.2%	70.8%	60.9%
		Pre-selection (AE)	80.5%	68.3%	58.8%

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Table 3-4 Computational time comparisons for different networks

Test Network			Test Network2	Test Network 3	Test Network 4
Computational time (seconds)	Distributed pattern	Optimal (ILP)	2.3	18.7	202.4
		ER-based unity- <i>p</i> -cycle	0.15	0.18	3.2
		Pre-selection (TS)	0.81	1.2	56.8
		Pre-selection (AE)	0.82	1.1	56.6
	Centralized pattern	Optimal(ILP)	2.1	18.2	201.4
		ER-based unity- <i>p</i> -cycle	0.10	0.15	2.8
		Pre-selection (TS)	0.80	1.0	55.9
		Pre-selection (AE)	0.79	1.0	55.6

We have also studied three other networks where the candidate cycles are not subject to the length constraint. We assume that each node performs full wavelength conversion, i.e., a lightpath can be switched to an output fiber at any free wavelength, each span has two fibers for bi-directional transmission, and the number of wavelengths per fiber is 64. For each test case, we generate 10^3 lightpath requests matrices. Table 3-3 compares the average redundancy obtained by different methods for both traffic patterns described above. The computational time of each method is presented in Table 3-4. As shown in these tables, the computational time for the *ER-based unity-*p*-cycle design* is much lower than the other methods based on ILP, and the redundancies obtained by the *ER-based unity-*p*-cycle design* differ from the optimal ones by 2% to 10% for both traffic pattern; the pre-selection method is slightly better than the *ER-based unity-*p*-cycle design* for the distributed pattern, but it requires

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8% to 19% more redundancy than the optimal solution for the centralized pattern. The average difference between *ER-based unity- p -cycle design* and the optimal one will decrease with the average network node degree increases.

3.6 Some Improvements of ER-Based Unity- p -Cycle

Heuristic

To improve the performance of *ER-based unity- p -cycle* heuristic, the following approaches have been employed separately or combined together.

- (1) Selection of the cycle with the largest number of nodes.

In the previous Section, the p -cycle is chosen one by one in the ascending order of the redundancy ratio. For multiple cycles with the same redundancy ratio, one of them is selected randomly. In this Section, instead of random selection, the cycle with largest number of nodes is selected. This is because the number of working links to be protected by a cycle is proportional to that cycle's node number. Thus by choosing cycles with largest number of nodes, more links can be protected in those cycles, and the overall number of cycles required in protecting all the working demands can be reduced. This will not only enhance the speed, but also improve efficiency of spare capacity.

- (2) To choose multiple cycles at one step.

Multiple cycles can be selected to protect at one time so as to improve the speed. When we choose one unit- p -cycle, the ER of the other unit- p -cycles may change. Hence if we choose multiple cycles at one time, the redundancy may increase. In this

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Section will focus on 2 cycles (duo-cycle) to be selected simultaneously and also present some simulation results on multiple cycles to explore the trade-off between computational time and redundancy.

3.6.1 Single-Cycle Selection

As mentioned before in Section 3.3, during the process of p -cycle selection, we will first select cycle with the maximum efficiency ratio. If it so happens that two or more cycles have the same maximum ER, we consider three criteria to select the unit- p -cycle. Firstly, we can choose the one with largest number of nodes which means this unit- p -cycle can protect more working units than other unit- p -cycles which have same ER with it (case 1). Secondly, we can choose the one with smallest number of nodes which means this unit- p -cycle has smaller spare capacity than other unit- p -cycles which have same ER with it (case 2). Thirdly, to simplify the algorithm, we can also randomly choose a cycle with the maximum efficiency regardless of its size (case 3). These three cases are selected because they are representative and include the best possible choice. However, which choice is the best is still unknown until the numerical studies are carried out. Table 3-5 shows the performance comparisons of these three different criteria for test network COST239.

Here, $L_{\max}$ denotes the maximum allowed cycle length used in protection; TSC denotes the total spare capacity needed, whereas TWC is the total working capacity; R is the redundancy ratio, which is defined as the total spare capacity divided by the total working capacity; N denotes the number of selected unit- p -cycles; D , duration in seconds, is the computational time merely for the selection of p -cycles. The time for

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cycle search and lightpath demand routing are not included in. All the decimal points are rounded up to 3 digits.

Table 3-5 Performance comparisons of these three different cases for TWC=704

L_{max}		4000	4500	5000	5500	6000	6500	7000	Infinity
Case 1	TSC	369	351	313	298	277	281	280	280
	R	0.524	0.499	0.445	0.423	0.393	0.399	0.398	0.398
	N	52	51	40	34	33	31	33	33
Case 2	TSC	376	351	311	303	277	283	281	281
	R	0.534	0.499	0.442	0.430	0.393	0.402	0.399	0.399
	N	57	51	45	37	35	33	34	34
Case 3	TSC	369	351	310	298	276	281	279	279
	R	0.524	0.499	0.440	0.423	0.392	0.399	0.396	0.396
	N	53	52	44	36	35	33	33	33
D (seconds)		0.032	0.062	0.063	0.109	0.140	0.156	0.171	0.187

From the results, it is first noted that when we allow cycles to have more physical length, more cycles are available for the selection of protection. Therefore, the redundancy becomes better. The ratio is at a minimum when the limiting length is set to be infinity. Comparing the results obtained from the three cases, it can be observed that when the cycles are constrained to a length of 4000 km, the 704 working units require 52 cycles to protect all the working units for Case 1; whereas in Case 2 the number of cycles increases to 57. In Case 3, the number of cycles is 53. Each time when a cycle is selected, the C program will loop once to re-calculate and rank the efficiency ratios of each cycle, then select the adequate cycle. If more cycles are selected to protect the same amount of working units, and the number of candidate cycles is same, then more loops of the program will be executed and the computational time would increase.

Another observation is that, since the sequence in cycle selection is different, the resultant total spare resources that need to be reserved and the redundancy will also be

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slightly different. This comparison is shown in Figure 3-6. The three curves are almost overlapping with each other so that we can ignore the minor differences between the three cases. Therefore, in the following, we will only consider the case where the cycle with largest number of nodes is chosen for each selection made to protect the required working capacity.

Figure 3-6 Comparisons of performances for three different selection criteria

Figure 3-7 Examples to illustrate the relationship of two cycles at each selection (a)

two independent cycles (b) two dependent cycles

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3.6.2 Duo-Cycle Selection

Another approach to improve the computational time is to choose two cycles at each selection. In this case, all the cycles' efficiency ratio are ranked and compared. The two cycles with the maximum efficiency ratios are selected. Then the working matrix will be updated correspondingly by reducing the working capacity protected by each of the cycles.

The relationship between the two cycles (namely cycle 1 and cycle 2) can be classified into two types: independent and dependent. If the two cycles selected are independent (Fig. 3-7(a)), i.e. they do not protect same spans, it is equivalent as in single-cycle selection case to choose cycle 1 to protect first, and then choose cycle 2 in the next loop. Problem may occur when the two cycles can protect the working units on the same spans. An example is shown in Fig. 3-7(b), to simplify, we will look at the case where the cycles are in clockwise direction. The directional span 2→4 is a straddling span of cycle 1, and an on-cycle span of cycle 2. The working capacity on this link can be protected simultaneously by the two cycles (cycle 1: 4→5→1→2, cycle 2: 2-6-7-4). Suppose that at one selection, cycle 1 has the maximum efficiency ratio, and cycle 2 is the second best. If the working units on this shared link is greater than or equal to two, each of the cycle can be assigned one unit of working capacity to protect. In the case where there is only one unit of working capacity remaining on the shared link, although we select two cycles at one time, only one of the cycles is needed to protect the working lightpath on this link. Suppose that working unit is assigned to be protected by cycle 1, this then reduce the total number of working units that can be protected by cycle 2, i.e. these two cycles are dependent. At this time, the efficiency

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ratio of cycle 2 may not be the second maximum any more. Suppose that at this time, cycle 3's efficiency is better than cycle 2. Instead of choosing cycles 1 and 2 at this selection, choosing cycle 1 and cycle 3 saves more spare resources.

Another problem is that, in our duo-cycle selection case, when cycles 1 and 2 are selected, if cycle 2's efficiency ratio is less than cycle 1's efficiency ratio, it is equivalent to the case of single-cycle selection where we choose cycle 1 first, and then choose cycle 2. However, in single-cycle selection program, as long as none of the working units on cycle 1's protecting span is reduced from one to zero, the cycle's efficiency ratio will remain unchanged. It will be selected repeatedly until the efficiency ratio is changed. That means that this duo-cycle selection approach may not choose the unit-*p*-cycle with maximum ER, hence the redundancy ratio achieved by duo-cycle selection approach may be worse than the previous result.

Table 3-6 lists the overall redundancy ratio (*R*), the redundancy difference (*D*) to the single-cycle selection as well as the 95% CI of the redundancy difference to the single-cycle selection for test network COST 239. Comparisons of computational time for single-cycle and duo-cycle selections are presented in Fig. 3-8. In the simulation, we assume that each node performs full wavelength conversion, i.e., a lightpath can be switched to an output fiber at any free wavelength, each span has two fibers for bi-directional transmission, and the number of wavelengths per fiber is 64. For each test case, we generate 1000 demand matrices and the number of lightpaths between any two nodes is selected from 1 to 10 (both inclusive) using a uniform random distribution.

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Table 3-6 Duo-cycle selections: results of average performances for 1000 demand

Matrixes

L_{max}	4000	4500	5000	5500	6000	6500	7000	Infinity
R	0.550	0.493	0.430	0.415	0.407	0.405	0.404	0.403
D	0.016	0.031	0.032	0.047	0.063	0.078	0.094	0.093
95% CI	0.02	0.03	0.01	0.02	0.01	0.03	0.02	0.01
CI	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.04

As shown in Table 3-6 and Fig. 3-8, the redundancy ratio obtained from the duo-cycle selection is slightly higher than that of single-cycle selection within a difference less than 5% for various allowed cycle lengths with 95% CI. When the cycle length approaches infinity, the computational time reduces from 0.125 to 0.093 seconds.

Figure 3-8 Comparisons of computational time for single-cycle and duo-cycle selections

We can easily extend the concept of the duo-cycle selection to a multiple-cycle selection, which means we can select three, four or any number of cycles at each loop.

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As the same with the duo-cycle selection, if the selected multiple cycles can protect same edges, it will not efficient as the single-selection. The computational time and redundancy comparisons are shown in Table 3-7. In the simulation, we choose COST 239 network as the test network and the maximum allowed cycle length is infinity. We also assume that each node performs full wavelength conversion, i.e., a lightpath can be switched to an output fiber at any free wavelength, each span has two fibers for bi-directional transmission, and the number of wavelengths per fiber is 64. For each test case, we generate 1000 demand matrices and the number of lightpaths between any two nodes is selected from 1 to 10 (both inclusive) using a uniform random distribution. As shown in Table 3-7, the redundancy increases with the increase in the number of selected cycles and the computational time decreases with the reduction in the number of selected cycles. When the number of selected cycles at one time is 5, the 95% CI of the redundancy difference is 0.11~0.16 and the computational time is reduced to 0.052 seconds. Therefore, if the network resource for protection is limited, we can use single-cycle selection method to work out the candidate *p*-cycles, whereas in the situations where speed is more of a concern, we could employ the multiple-cycle method to achieve a faster protection and restoration.

Table 3-7 The performance comparisons for the multiple cycle selection

Number of selected cycles at one time	Computational time(s)	Average redundancy	95% CI of the rudandancy difference to the single-cycle selection
2	0.093	0.404	0.01 ~ 0.04
3	0.072	0.451	0.05 ~0.10
4	0.063	0.483	0.07 ~ 0.12
5	0.052	0.521	0.11~0.16

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3.7 Summary

In this chapter, we have proposed a new design heuristic, i.e., the *ER-based unity-p-cycle design*, for the construction of survivable WDM networks without using ILP. To evaluate the effectiveness of this new heuristic, we have studied four networks and compared the redundancies obtained by different methods under two different traffic patterns. The study has shown that the new heuristic performs well for both traffic patterns, and the redundancies obtained by the new heuristic are very close to that of the optimal solution with much reduced computational time.

To reduce the computational time, several modifications were also suggested to this heuristic algorithm. The first modification is that when several cycles with the same efficiency ratio, we always choose the cycle with the largest number of nodes. The second is that we choose multiple cycles simultaneously at one time. The results obtained with these modifications are then compared with previous results.

Chapter 4 Strategies for Design of Dynamically Survivable WDM Optical Network with *P*-Cycles

4.1 Introduction

In order to design survivable WDM optical networks, network resources have to be allocated effectively. Two different kinds of traffic models, namely static traffic and dynamic traffic have been considered for such networks. In the static traffic model, lightpath requests are known in advance, so the primary lightpath and backup lightpath can be computed off-line either through integer linear programming (ILP) methods or heuristic methods to achieve optimal or sub-optimal solutions. The study of network design with static traffic model is useful for network planning. However demand is usually not static but changes dynamically. This means that working lightpaths and hence protection lightpaths will have to be established and torn down dynamically in accordance with the changing traffic demand. The ILP method is time consuming and not scalable based on the current computational power and may not be suitable for on-line computation. As reported in [80], the average processing time per connection request is 0.5 seconds for a 15-node network with 200 requests (using a PC

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with a 1.5GHz CPU); the average processing time per connection request quickly increases to 8.5 seconds for a 46-node network with 200 requests. Hence, for dynamic traffic model, fast on-line heuristic methods are usually used [83], [85], [86], [88].

Future WDM optical networks are foreseen to be more dynamic and sensitive to failures. Therefore, dynamic service provisioning with network survivability becomes a critical requirement for network planning and management [79], [81]-[83]. For dynamic traffic model, lightpath requests come and go dynamically and no knowledge of future arrivals is available at the time of provisioning current lightpath requests. The approach of shared backup path protection (SBPP) has been intensively studied as the solution to the problem of network survivability under such a dynamic scenario [84]-[87]. This is primarily because the SBPP approach can achieve a significant reduction in spare capacity by sharing the spare capacity across multiple failure-independent connections. However, because resources along the protection paths are shared, cross-connects along the protection paths are not configured at the connection setup; instead they are only configured when a failure actually occurs. This introduces additional delays to signal to the intermediate nodes and configure them, thus increasing restoration time significantly compared to those methods where protection paths are pre-configured (pre-fixed) for the intermediate nodes.

As described in Chapters 2 and 3, the p -cycle method is very attractive in that it can achieve ring-like fast protection and mesh-like high efficiency in the use of spare capacity [54]. So far the p -cycle design method has been extensively studied for design of survivable WDM networks with static traffic model. As presented in Chapter 3, either ILP models or heuristic methods have been developed for static network

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designs. However, very little work on dynamic p -cycles design has been reported. In this chapter, we extend *ER-based unity- p -cycle design* heuristic described in Chapter 3 to configure dynamic p -cycles that are adaptive to dynamically changing traffic demand in optical networks. We consider three strategies for dynamically configuring p -cycles and compare their performance under two different traffic patterns by computer simulations. The results show that one of these strategies can even achieve a blocking performance almost as good as that of the SBPP scheme [85], [86] but with a much faster restoration speed.

4.2 Dynamic p -Cycles Design

We now apply the *ER-based unity- p -cycle design* heuristic presented in Chapter 3 to design of survivable optical networks with dynamic traffic demands. In a dynamic network, lightpath requests arrive and depart the network dynamically. When a new lightpath request arrives at the network, it is first routed and assigned with available wavelengths along a path selected using any efficient routing and wavelength assignment algorithm (RWA) one prefers to use, such as shortest path routing [74] and first-fit wavelength assignment [4], [5]. Once the new lightpath has been successfully set up, the *ER-based unity- p -cycle design* heuristic is employed to configure p -cycles to provide protection. Therefore, when a new lightpath request arrives, the p -cycle design for dynamic traffic model can be divided into the following two steps:

Step-1: Use an efficient routing and wavelength assignment algorithm to route the lightpath request and assign a wavelength to the request; if the lightpath cannot be set up, this new request is blocked.

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Step-2: If Step 1 is successful, the *ER-based unity- p -cycle design* heuristic algorithm is used to configure p -cycles. If the network does not have enough spare capacities for this, then this new request is blocked.

Depending on whether all the existing p -cycles are released and then reconfigured, we consider three strategies for dynamically configuring p -cycles.

Figure 4-1 The flowchart of Strategy-1

Strategy-1: When a new lightpath request arrives, we release all previously configured p -cycles, and attempt to set up the new lightpath using an efficient RWA algorithm. If this is successful, we reconfigure p -cycles using the *ER-based unity- p -cycle design* heuristic to provide full protection for all the existing lightpaths as well as the new lightpath. Note that in this case, the new lightpath setup is made based on all free wavelength channels, including those released from the previously configured p -cycles. For an example, if the number total wavelength channels on each edge is 16,

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on edge 1, 5 wavelength channels were used for existing lightpaths, and 5 wavelength channels are used to configure *p*-cycle, hence the left wavelength channel on edge 1 is $16-5-5=6$. In our Strategy-1, we will releasing all configured *p*-cycles, so the new lightpath setup is made based on $16-5=11$ wavelength channels on edge 1. The flow chart of strategy-1 is given in Fig. 4-1.

Figure 4-2 The flowchart of Strategy-2

Strategy-2: When a new lightpath request arrives, we first attempt to set up the new lightpath using an efficient RWA algorithm but without releasing all previously configured *p*-cycles. If this is successful, we will check whether the existing *p*-cycles is able to provide protection for the new lightpath. If it dose not, we configure some new unity-*p*-cycles and use both the existing and newly configured *p*-cycles to provide full protection. Unlike Strategy-1, all the previously configured *p*-cycles are kept and the new lightpath can only be set up in the remaining free capacities of all the links excluding those of the exiting *p*-cycles. For an example, if the number total wavelength channels on each edge is 16, on edge 1, 5 wavelength channels were used for existing lightpaths, and 5 wavelength channels are used to configure *p*-cycle,

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hence the left wavelength channel on edge 1 is 16-5-5=6. In our Strategy-2, the new lightpath setup is made based on 16-5-5=6 wavelength channels on edge 1. The flowchart for Strategy-2 is shown in Fig. 4-2.

In order to efficiently make use of the existing p -cycles, the selection of a route for a new lightpath attempts to maximize the number of work units that can be protected by the existing p -cycles. In order to do so, we need to modify the cost of each link for the setup of the new lightpath in **Step-1**. The details are described as follows.

We first define some notations and then present the new cost function for each link. A network is represented as a weighted, directed graph $G = (V, E, C, \lambda)$, where V is the set of nodes, E is the set of unidirectional links, $C(e)$ is the cost function of each link e and λ_e specifies the number of wavelength channels on each link.

P represents the set of the existing p -cycles. The parameter x_{ij} indicates if the working units on edge j can be protected by p -cycle i , where $x_{ij}=1$ if the working units on edge j can be protected by p -cycle i , otherwise $x_{ij}=0$. n_i represents the number of wavelength channels in the i^{th} existing p -cycle, $i \in P$. w_e is the number of working wavelength channels on link $e \in E$. We use w_e^p to denote the number of working wavelength channels protected by the existing p -cycles on link $e \in E$ ($w_e^p = \sum_{i \in P} x_{ij} n_i$).

λ_e^f denotes the number of free wavelength channels on link e . The new cost function of each link is defined as below:

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$$C^{new}(e) = \begin{cases} C(e) & \text{if } (\lambda_e^f > 0) \wedge (w_e = w_e^p) \\ 0.5 \times C(e) & \text{if } (\lambda_e^f > 0) \wedge (w_e < w_e^p) \\ +\infty & \text{otherwise} \end{cases} \quad (4-1)$$

Here we assume each work unit need one spare unit to provide protection. The first case $(\lambda_e^f > 0) \wedge (w_e = w_e^p)$ implies that the current configured p -cycles cannot provide protection for one more working wavelength channel on link e . Hence using this link for the new working lightpath will need one working unit and one spare unit, the cost of link e in this case is the same as the original one $\frac{(1+1)}{2} \times C(e) = C(e)$. The second case $(\lambda_e^f > 0) \wedge (w_e < w_e^p)$ indicates that the current configured p -cycles can still protect one more working wavelength channel on link e . Hence the use of link e for the new working lightpath will only need one working unit and zero spare unit, the cost of link e in this case is reduced to $\frac{(1+0)}{2} \times C(e) = 0.5C(e)$, instead of $C(e)$. That is, link e is a preferred choice as it induces a lower cost. The last case implies that there is no free wavelength channel on link e , so the cost of this case is $+\infty$.

Our studies have shown that Strategy-1 can achieve a better blocking performance than Strategy-2, since all the existing p -cycles are freed up and then reconfigured upon a new lightpath arrival [89]. However, Strategy-2 requires much less computational time than Strategy-1, since it only requires configuring some new unity- p -cycles to provide protection for the new lightpath. In view of the pros and cons of both Strategy-1 and Strategy-2, we propose a third strategy (Strategy-3), which combines the advantages of both Strategy-1 and Strategy-2 and hence it is expected to achieve the best performance.

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Figure 4-3 The flowchart for Strategy-3

Strategy-3: When a new lightpath request arrives, we first attempt to set up the new lightpath as in Strategy-2. If this is successful, Strategy-2 is employed to configure some unity- p -cycles; otherwise all the existing p -cycles are released and Strategy-1 is used to set up a new lightpath for the new request and reconfigure p -cycles to protect all existing and new lightpaths. The flowchart for Strategy-3 is shown in Fig. 4-3.

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Figure 4-4 Topology of test networks

4. 3 Numerical Results

We have chosen the pan-European COST 239 network [75], [76] and NSFNET network [90] as test networks, as shown in Fig. 4-4. Without loss of generality, we assume that each node performs full wavelength conversion [91], [92] (i.e., a lightpath can be switched to an output fiber at any free wavelength), each span has two fibers for bi-directional transmission, and the number of wavelengths per fiber is 16. It may be noted that the networks considered are virtual wavelength path networks (VWP networks) [91]. In our simulations, we assume that lightpath requests arrive at the network according to a Poisson process and the holding time of lightpaths is exponentially distributed [102]. Let λ be the arrival rate and $1/\mu$ be the average holding time. Then total network traffic load is λ/μ and the average traffic load per node is $\lambda/(\mu N)$ where N is the number of nodes in the network. For the case of Poisson process with average arrival rate of λ , the inter-arrival time is a exponential

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distribution with a mean inter-arrival time of $1/\lambda$. In order to create a Poisson process with a mean arrival rate of λ [102], we have to use a random number generator to create a random number v in $[0, 1]$. We then calculate the inter-arrival time for the next arrival using $-(1/\lambda)\ln(v)$. To generate the hold time of each lightpath, we also use a random number generator to create a random number v in $[0, 1]$, then calculate the holding time of each lightpath using $-(1/\mu)\ln(v)$. We consider two different traffic patterns:

- (i) Distributed pattern: lightpath requests are uniformly distributed among all node pairs, i.e., any two different nodes are equally likely to be a source-destination pair for a lightpath request. For each lightpath request arrival, we assign the source-destination pair to it equally. Hence, the average traffic load per node pair is $\lambda/(\mu N(N-1))$, where N is the number of nodes in the network.
- (ii) Centralized pattern: each node has lightpath demands only from and to a central node and the demands between the central node and the other nodes are distributed uniformly. In our simulation, we choose node 1 as the central node. Only the node pair $(a, b) \in \{(1, j), (j, 1), 2 \leq j \leq N\}$ can be a source-destination pair for a lightpath request. And for each lightpath request arrival, we assign the source-destination pair $(a, b) \in \{(1, j), (j, 1), 2 \leq j \leq N\}$ to it equally. Hence, the average traffic load per node pair for pair $(a, b) \in \{(1, j), (j, 1), 2 \leq j \leq N\}$ is $\lambda/(2\mu(N-1))$ and it is zero for other node pairs.

The lightpath requests are routed based on the Dijkstra's algorithm [74] with cost of each link reciprocal to the free capacity of the span [60]. The cost function of each link is:

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$$C_1(e) = \begin{cases} 1/\lambda_e^f & \text{if } \lambda_e^f > 0 \\ \infty & \text{otherwise} \end{cases} \quad (4-2)$$

Figure 4-5 Blocking probability vs. number of arrived lightpath requests

We use the metrics: blocking probability, redundancy and link utilization to measure the performance of the proposed strategies. The total number of lightpath requests generated is 10^6 for each traffic load in the simulation. For each traffic load, we choose the first 10^5 lightpath requests as warm-up period, Fig. 4-5 shows the blocking probability for every 100000 lightpath requests after the first 10^5 lightpath requests for COST 239 network with the distributed traffic pattern and the total traffic load is 253 (the traffic load per node is 23). As demonstrated in Fig. 4-5, the blocking probability of each method is almost fixed at one value; the relative variation of blocking probability is less than 4%. Hence after the first 10^5 lightpath requests, the network

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has already reached the steady state. The following performance comparisons are based on the average results after the first 10^5 lightpath requests.

4.3.1 Blocking Probability

Figs. 4-6 and 4-7 show the blocking probability versus offered traffic load per node for different strategies for the COST239 and NSFNET networks, respectively. For NSF Network, the average node degree (i.e., the number of links connected to a node) is 3, but it is 4.7 for COST 239 network. This means that the connectivity of COST239 network is much higher than NSFNET. As a consequence, COST239 network can support a much higher offered traffic load than NSF network for a given blocking probability. The blocking probability for an effective Full Information Routing (FIR) approach of shared backup path protection (SBPP) scheme [85] is also shown in these figures for comparison purpose.

In our simulation, when a new lightpath request arrives, the FIR-SBPP approach first computes a least-cost path as the working lightpath based on the Dijkstra's algorithm [74] with the cost function $C_1(e)$ in (4-2) and then computes as a backup path with a least-cost based on the Dijkstra's algorithm [74] with based on the Dijkstra's algorithm [74] with the cost function $C_2(e)$ in (4-3), which is described below. Let parameter v_i^j represent the number of working paths that traverse link j and are protected by link i (and their corresponding backup paths traverse link i). Hence, the number of wavelength channels reserved for backup paths on link i is $v_i^* = \max\{v_i^j, \forall j \in E\}$. Let l_w represent the current working path. The cost function $C_2(e)$ is defined as follows:

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$$C_2(e) = \begin{cases} +\infty & \text{if } e \in l_w \\ +\infty & \text{if } \lambda_e^f = 0 \wedge (\exists j \in l_w, v_e^j = v_e^*) \\ \varepsilon \times C_1(e) & \text{if } \forall j \in l_w, v_e^j < v_e^* \\ C_1(e) & \text{otherwise} \end{cases} \quad (4-3)$$

The first case ($e \in l_w$) indicates that link e is traversed by the working path. Since the backup path has to be link-disjoint with the working path, the cost of this case is $+\infty$. The second case implies that link e needs to be allocated a free wavelength to protect current working path. As there is no free wavelength channel on link e , the cost of this case is also $+\infty$. In the third case, link e does not need to be allocated any more free wavelength channel to protect the current working path, so the cost of this case is $\varepsilon \times C_1(e)$. Here ε is a small number. ε is used instead of 0, so that among multiple paths with 0 cost, the minimum hop path is chosen. The last case implies that there are still free wavelength channels on link e and link e needs to be allocated a free wavelength to protect the current working path, hence the cost for this case is the original one $C_1(e)$.

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 4-6 Comparison of blocking probability performance of different strategies for COST239 Network

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 4-7 Comparison of blocking probability performance of different strategies for the NSF Network

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As shown in figures 4-6 and 4-7, Strategy-3 achieves the lowest blocking probability among the three proposed strategies and its blocking probability is almost the same as that of the FIR-SBPP approach. In Strategy-3, the advantages of release are preserved and the cost of each link for setting up a new lightpath in **Step-1** is modified to make use of the existing p -cycles efficiently, hence it can achieve lowest blocking probability. The blocking performance of Strategy-2 is the worst among the three strategies. For centralized traffic pattern, the distribution of traffic load per link is imbalanced. The links connected to the central node (the central node is one end of the link) have much higher traffic load than other links. The block occurs when these links are jammed. Hence the offered traffic load for distributed traffic pattern is much higher than that for centralized traffic pattern.

4.3.2 Redundancy

Another metric for comparing resource efficiency is the redundancy, which is defined as the sum of all wavelengths on all the links consumed by the p -cycles (the backup paths for the SBPP) over the sum of all wavelengths of all the links utilized by the working paths. The redundancy is also called resource overbuild in [85]. The redundancy indicates the amount of extra resources needed for protection provisioning as the percentage of the amount of resources required without providing protection. Figs. 4-8 and 4-9 show the redundancy versus offered traffic load per node for different strategies for the COST239 and NSFNET networks, respectively. As shown in these figures, Strategy-3 achieves the lowest redundancy among the three proposed strategies. For Strategy-2, the configured p -cycles will never be released. Hence the redundancy of Strategy-2 is much higher than other approaches.

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 4-8 Comparison of redundancy performance of different strategies for COST239 Network

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 4-9 Comparison of redundancy performance of different strategies for the NSF Network

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4.3.3 Link utilization

In Figs. 4-10 and 4-11, the link utilization is plotted as the function of the offered traffic load per node for the COST239 and NSFNET networks, respectively. In our simulation, the link utilization is the ratio of the total used capacity to the total capacity: $\sum_{e \in E} (w_e + s_e) / \sum_{e \in E} c_e$, where w_e , s_e and c_e are the working units, spare units and total units on edge e , respectively. As shown in these two figures., the link utilization increases with the traffic load. The Strategy-2 has much higher link utilization than the other approaches. For a given offered traffic load, a lower link utilization means that there is more free capacity in the network and hence a lower blocking probability can be achieved.

Figure 4-10 Comparison of link utilization for different strategies for the COST239

Network

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Figure 4-11 Comparison of link utilization for different strategies for the NSF Network

4.3.4 Computational Complexity

We next compare the computational complexity for different schemes. For each lightpath request, the computational complexity of dynamic traffic model can be divided into two parts. The first part is the computational complexity for the working lightpath setup in **Step-1**. In our simulation, the computational complexity of this part is $O(N^2)$ [85] for all the four approaches, where N is the number of nodes in the network. The second part is the computational complexity for configuring p -cycles to provide protection or setting up the backup path for the FIR-SBPP). For Strategy-1, the computational complexity of the second part is $O(W \times E \times M)$, where W is the

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number of wavelength channels per fiber, E is the number of edges in the network and M is the number of candidate cycles. Here we consider the worst case, each unit- p -cycle just protected 1 working unit, the total working units is less than $W \times E$, hence the total number of loops of our *ER-based unity- p -cycle design* is less than $W \times E$. For each loop, we need calculation ER of M cycles, so the total number calculation is less than $W \times E \times M$. For Strategy-2, the total working units of the new light path is less than $(N-1)$, the total number calculation is less than $(N-1) \times M$, hence the computational complexity of the second part is $O(N \times M)$. For Strategy-3, it combines Strategy-1 and Strategy-2. We assume p is the probability of employing Strategy-1 to configure p -cycles (the probability of release). The average computational complexity of the second part for Strategy-3 is then given by:

$$p \times O(W \times E \times M) + (1 - p) \times O(N \times M) \tag{4-4}$$

Table 4-1 The probability of release in Strategy-3

Distributed traffic pattern			Centralized traffic pattern		
Traffic load	number of releases	Probability of release	Traffic load	number of releases	Probability of release
21	402	0.00040	4.5	523	0.00052
22	1065	0.00106	5	1274	0.00127
23	3196	0.00320	5.5	3468	0.00347
24	7221	0.00722	6	7582	0.00758
25	13705	0.01371	6.5	14211	0.01421
26	29273	0.02927	7	30100	0.03010
27	56716	0.05671	7.5	57818	0.05782
28	73854	0.07385	8	75685	0.07569
29	81262	0.08126	8.5	85694	0.08569
30	88938	0.08894	9	91025	0.09103

Here the release number is the number of calculations based on Strategy-1. The total number of lightpath requests is 10^6 , hence the probability of release is given by (release number)/ 10^6 . The number of calculations based on Strategy-2 is (release number). The probability of release for the test network COST 239 is shown in Table

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4-1. Table 4-1 clearly illustrates that the probability of release increases as the traffic load increases and it is less than 10% in our simulation. Hence the average computational complexity of Strategy-3 is expected to be close to that of Strategy-2 when network traffic load is not too high (i.e, the blocking probability is not higher than 0.1). For the FIR-SBPP approach, the computational complexity of the second part is $O(E^2)$ [85].

For every successful lightpath in our simulation for test network COST239, the average computational time is approximately 60 ms for Strategy-1; whereas the average computational time is approximately 6 ms for Strategy-2, 8 ms for Strategy-3 and 0.1ms for the FIR-SBPP approach. Note that the computing platform used is Intel Pentium IV 2.4GHz PC running Windows 2000 with 512 MB memory and 40GB hard disk. It should be noted that as compared with the SBPP approach [85], [86], the advantages of the *p*-cycle-based protection lie in its fast restoration speed and simplicity of its signaling process. This is because, after a link failure, the SBPP in [85], [86] needs a complex signaling process to inform multiple relevant nodes of failed primary lightpaths so that they can be switched to the backup lightpaths, and hence it requires a much longer restoration time. In contrast, with the *p*-cycle-based dynamic protection, only the two nodes adjacent to the failed link are involved in protection switching and all the *p*-cycles are pre-configured. Therefore, the restoration speed is very fast and will be of the order of 50 ms as in conventional SONET/SDH rings.

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4.5 Conclusions

We have considered the problem of survivable WDM networks under dynamically changing traffic demands and extended our previously proposed *ER-based unity- p -cycle design* heuristic to solve this problem. We have presented three strategies to dynamically configure p -cycles that are adaptive to changing traffic demand. The blocking performance, redundancy and link utilization performance for these strategies have been studied through computer simulation under two different traffic patterns for two different test networks. The results have shown that Strategy-3 achieves the lowest blocking, redundancy and link utilization performance among the three strategies. Blocking performance of Strategy-2 is much worse than that of Strategy-3 but since Strategy-2 does not release any configured p -cycles, it achieves much higher redundancy than the other two strategies. However, Strategy-1 has a better blocking performance than Strategy-2. The simulations also reveal that the blocking probability of Strategy-3 is the almost the same as that of the SBPP scheme. Since it is based on the p -cycle scheme, when failure occurs, only the two end-nodes of the failed link will need to take action on failure; it can, therefore, achieve much faster restoration speed than the SBPP.

We also analyze the computational complexity for different schemes. For each lightpath request, the computational complexity of three strategies are $O(N^2) + O(W \times E \times M)$ for Strategy-1, $O(N^2) + O(E \times M)$ for Strategy-2 and $O(N^2) + p \times O(W \times E \times M) + (1 - p) \times O(N \times M)$ respectively, where N is the number of nodes, E is the number of edges, W is the number of wavelength channels per fiber and M is the number of candidate cycles, p is the probability of employing Strategy-1

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to configure p -cycles. It is clear that the computational complexity of Strategy-1 is much higher than the other two strategies. This is because, for Strategy-1, when a new lightpath arrives, all the existing p -cycles are freed up and then reconfigured to provide protection for all working units on each edge. For Strategy-2, it only configures p -cycles to provide protection for the working units on the edges which are traversed by the newly established lightpath. Hence Strategy-2 has lowest computational complexity. For Strategy-3, it combines Strategy-1 and Strategy-2. Its computational complexity depends on p (the probability of employing Strategy-1 to configure p -cycle). In our simulations, p is less than 10%. Hence the average computational complexity of Strategy-3 is close to that of Strategy-2.

Chapter 5 Dynamically Survivable WDM Network Design with *P*-Cycle-Based PWCE

5.1 Introduction

In chapter 4, we have introduced the design problem of survivable WDM networks with dynamic traffic demands and extended our proposed *ER-based unity-p-cycle design* heuristic to solve this problem. In this chapter, we aim at simplifying network management and reducing processing overhead by modeling this design problem using a *p*-cycle-based *protected working capacity envelope* (PWCE) approach [95]-[99]. We present a new integer linear program (ILP) to solve the *p*-cycle-based PWCE design problem for dynamically survivable WDM networks and provide quantitative results on the performance of this design problem.

The concept of *protected working capacity envelope* (PWCE), originally introduced by Grover in [93], [94], is attractive because it does not need protection resources to be dynamically configured thereby simplifying network management and reducing

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processing overheads. For a given network topology with the specified edge (span) capacities, it first assigns some spare capacity to each edge to create an “envelope” of protected working capacities. As a result, any dynamically arriving lightpath demand routed within this PWCE is automatically protected. This eliminates the process of finding protection paths for dynamically arriving traffic demands. Once the PWCE is determined for a given network, the issue remaining is to simply route dynamically arriving traffic demands within the already determined PWCE in the network.

Figure 5-1 An example showing the PWCE concept

Fig. 5-1 illustrates the PWCE concept, where the physical total capacity is divided into two parts: the spare capacity (s_i) and the protected working capacity (w_i). These two parts create two layers, i.e. a spare capacity layer and a protected working capacity layer, as shown in Fig. 5-1. The protected working capacity in each span creates a *capacity envelope* that is protected by the capacity in the spare capacity layer. This created *capacity envelope* is called *protected working capacity envelope* (PWCE). If the working path is routed in the PWCE that is thus created, it is automatically protected by the capacities in the spare capacity layer. Service provisioning for

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dynamically arriving traffic demands is simplified as it is then equivalent to routing a new path in a previously non-protected network.

5.2 Principle of p -Cycle-Base PWCE Design

For a given network topology, the PWCE design problem is how to assign the spare capacity and the working capacity on each edge. Since this design problem is an optimization problem without knowing the actual traffic demands and needs to be done before setting up working lightpaths, it is obviously that this problem can be solved with a link-based protection approach. By incorporating the advantages offered by p -cycles as described in Chapter 3, we consider here a p -cycle-based PWCE approach [95]-[99] to solve this design problem.

For a p -cycle-based PWCE, spare capacities are pre-allocated to each edge to configure p -cycles so that an “envelope” of protected working capacities can be created with pre-determined p -cycles. A dynamically arriving traffic demand may be routed in this pre-determined protected working capacity envelope using any efficient routing algorithm that one prefers to use. A dynamically survivable WDM network is then designed with the following two steps:

Step-1: Allocating spare capacity on each edge to configure p -cycles; PWCE can then be created with those pre-configured p -cycles. This is an off-line processing step.

Step-2: Routing dynamic traffic demands in the pre-created PWCE using any efficient routing algorithm (e.g. shortest path). This is an on-line processing step.

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Figure 5-2 An example of p -cycle-base PWCE showing one bi-directional p -cycle with 4 spare units and the corresponding protected working capacity envelope

Fig. 5-2 shows a simple example of p -cycle-based PWCE design where a bi-direction p -cycle (1-2-3-4-5-6-1) is configured with 4 spare units on each on-cycle edge so as to create a PWCE. This p -cycle protects 4 working units on an on-cycle edge and 8 working units on any straddling edge. Note that all edges are bi-directional. As shown in Fig. 5-2(b), this p -cycle creates a PWCE with 4 protected working units on each of edges 1-2, 2-3, 3-4, 4-5,5-6 and 8 working units on each of edges 1-5, 2-5 and 2-4.

5.3 ILP Formulation for p -Cycle-Based PWCE Design

The problem of p -cycle-based PWCE design can be solved with ILP formulation, since it is step-1 (an off-line processing step) for dynamic protection provisioning in

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WDM optical networks. The objective is to maximize the total protected working capacity in the PWCE.

The current network may have transmission link systems with equal capacities in both directions. In future optical networks, traffic demands (e.g., broadcast or multicast traffic, data retrieval from databases and websites) may not be identical between any two nodes; some nodes may be the locations of databases and frequently visited websites from there a huge amount of data may be delivered to some other nodes. This means that the lightpath demand between any two nodes is not necessarily equal in both directions. Therefore, it is important to consider a more generic network situation whose transmission capacity in each direction may not necessarily be equal and/or traffic demands between two nodes may not be identical. Under such network situations, the directed p -cycles model can handle both unidirectional and bidirectional traffic demands. However the bi-directed p -cycles model can not deal with unidirectional traffic demands, it can only handle bi-directional traffic demands. For the above reasons, we have proposed the directed p -cycle model and carried out detailed studies for its performance.

We model a WDM network as a directed graph $G(V, E)$ with V as the set of nodes and E as the set of directed edges. For a set of X , we use $|X|$ to denote the number of elements in the set. A directed edge transmits data in one direction. Any edge in the network may consist of two counter directional edges whose capacity may not be equal. We define a unit of capacity on a directed edge as one wavelength channel. We assume that a directed edge j contains l_j fibers of K wavelength channels each so that the capacity of edge j is $c_j = l_j \times K$. Let P denotes the set of all candidate directed p -

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cycles for a given network. A directed p -cycle can provide one backup path for every on-cycle edge in the opposite direction, and one backup path for any directed straddling edge. The efficiency of directed p -cycles remains the same as that of bidirectional p -cycles, since a straddling bi-directed edge here is considered as two directed edges in opposite directions. To illustrate this, let us consider an example shown in Fig. 5-3.

Fig. 5-3 (b) shows a directed p -cycle 1 in the counter-clock wise direction. When the on-cycle edge (or span) 1-4 fails (shown in Fig. 5-3 (c)), both directed edges $1 \rightarrow 4$ and $4 \rightarrow 1$ fail simultaneously. The directed p -cycle 1 can provide one backup path $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$ for directed edge $1 \rightarrow 4$, but it cannot provide backup path for directed edge $4 \rightarrow 1$. When the straddling edge 2-4 fails (shown in Fig. 5-3 (c)), both directed edges $2 \rightarrow 4$ and $4 \rightarrow 2$ fail simultaneously. The same directed p -cycle 1 can provide one backup path $4 \rightarrow 1 \rightarrow 2$ for directed edge $4 \rightarrow 2$ and one backup path $2 \rightarrow 3 \rightarrow 4$ for directed edge $2 \rightarrow 4$.

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Figure 5-4 An example illustrating that a unidirectional p -cycle offers one backup path for any on-cycle edge in the opposite direction and also one backup path for any directed straddling edge of the p -cycle.

Note that a bidirectional (or non-directed) p -cycle can always be formed by two counter-directional p -cycles, and a bidirectional edge consists of two counter-directional edges. In contrast to the approach of [95]-[97], we present our formulation using directed (or unidirectional) p -cycles [60], [69] and directed edges. This is because lightpaths are directional in nature and lightpath demands between node-pairs may not be identical in both directions in future WDM networks. In the rest of this Chapter, all p -cycles are meant to be directed p -cycles and all edges are directed edges. For a given network topology, the set of all candidate p -cycles can be pre-determined by the method in [72] (see details in Chapter 3). In the following, we first describe several variables and parameters used in our ILP model.

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s_j is the number of spare units required on edge j to configure p -cycles.

w_j is the number of protected working units on edge j . $w_{\max} = \max\{w_j, 1 \leq j \leq |E|\}$

and $w_{\min} = \min\{w_j, 1 \leq j \leq |E|\}$ are the max. and min. values of w_j , respectively.

α is the allowed maximum variation for all w_j 's (i.e. $w_{\max} - w_{\min} \leq \alpha$). α is a predetermined constant which restricts the variation of all w_j 's. We shall see in Section 5.4 that the value of α will affect the performance.

p_{ij} indicates if edge j is an element of p -cycle i or not; $p_{ij}=1$ if edge j is an element of p -cycle i , otherwise $p_{ij}=0$.

x_{ij} indicates if the working units on edge j can be protected by p -cycle i or not; $x_{ij}=1$ if the working units on edge j can be protected by p -cycle i , otherwise $x_{ij}=0$.

n_i is the number of spare units required for directed p -cycle i .

c_j denotes the total number of units on edge j (i.e. total capacity on edge j).

We assume that every node in the network can convert a wavelength on any input fiber to any other wavelength on any output fiber and hence the wavelength continuity of lightpaths is not required. The objective of the PWCE design is to maximize the amount of the protected working units for a given network with dynamic traffic demands [95]-[97]. In contrast to [95]-[97] where bidirectional p -cycles are considered, we use directed p -cycles and add a new constraint on the variation of w_j . The new modified ILP model for the PWCE design with directed p -cycles is given as follows:

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$$\text{Objective:} \quad \max \sum_{j=1}^{|E|} w_j \quad (5-1)$$

$$\text{Constraints:} \quad s_j = \sum_{i=1}^{|P|} p_{i,j} n_i \quad \forall j \in E \quad (5-2)$$

$$w_j \leq \sum_{i=1}^{|P|} x_{i,j} n_i \quad \forall j \in E \quad (5-3)$$

$$w_j + s_j \leq c_j \quad \forall j \in E \quad (5-4)$$

$$w_{\min} \leq w_j \leq w_{\max} \quad \forall j \in E \quad (5-5)$$

$$w_{\max} - w_{\min} \leq \alpha \quad (5-6)$$

Note that w_j represents the protectable working units on each directed edge; this is unknown, and will have to be determined by the above ILP model. The values of $p_{i,j}$, $x_{i,j}$, c_j , α , and the sets of P (directed p -cycles) and E (directed edges) can be pre-determined for a given network topology.

The objective in (5-1) is to maximize the total protected working units. The constraint in (5-2) allocates the required spare units on each edge. The constraint in (5-3) determines the protectable working units, and the one in (5-4) gives the capacity restriction on an edge. The constraints in (5-5) and (5-6) determine the maximum allowed variation of w_j . All variables in (5-1) – (5-6) are positive integers.

5.4 Simulation Results

We choose the pan-European COST 239 network [75], [76] and NSFNET network [90] as test networks. The topologies of these two test networks are shown in Fig. 4-4.

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Here we assume that each span has two fibers of 16 wavelengths per fiber transmitting in opposite directions. We also assume that the lightpath requests arrive at the network from a Poisson process and that the holding time of a lightpath follows a negative exponential distribution. Let λ be the arrival rate and $1/\mu$ be the average holding time. Then total network traffic load is λ/μ and the traffic load per node is given by $\lambda/\mu N$, where N is the number of nodes in the network. We further assume that lightpath requests are uniformly distributed among all node pairs, i.e., any two different nodes are equally likely to be a source-destination pair for a lightpath request. For each lightpath request arrival, we assign the source-destination pair to it equally. Hence, the average traffic load per node pair is $\lambda/\mu N(N-1)$.

It should be noted that the fact that the traffic is uniformly distributed does not imply that the lightpath request is bi-directional. A bi-directional lightpath request means that the request requires the establishment of two identical unidirectional light paths between two nodes (one from node i to node j , and the other from node j to node i). Uniformly distributed traffic means that a request generated at node i is equally likely to be directed to any of the other nodes in the network (i.e. that it is uniformly distributed among the nodes). Uniformly distributed traffic does not imply that a lightpath set up from node i to node j is always accompanied with another lightpath establishment from node j to node i . With uniformly distributed traffic, the average traffic load per node pair could be the same for a long observation time, but it does not mean the lightpath demands between any node-pair are always the same in both directions. In our simulation, the lightpaths generated are always unidirectional, that is, a lightpath generated at node i and addressed to node j does not accompany a new lightpath generated at node j and addressed to node i . In the simulation study, 10^6

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lightpath requests are generated for each traffic load. As explained in Section 5-2, the design of a dynamically survivable WDM network with *p*-cycle-base PWCE approach is done in two steps. First, the software CPLEX 8.0 [100] is used to find the solution for our ILP model (A brief explanation on how to use CPLEX is given in Appendix I). Our investigations show that the number of total protectable working units depends on the value of α . Table 5-1 shows the relationship between the number of total protected working units and α for the two test networks. As shown in Table 5-1, the number of total protected working units increases with increasing α , reaching the maximum at $\alpha = 2$ for the COST 239 network, and at $\alpha = 5$ for the NSF network.

Table 5-1 Relationship between the number of total protectable working units and α

α		0	1	2	4	≥ 5
COST 239	No. of total protectable working units	624	642	656	656	656
NSF		336	370	402	426	430

In the second step of our design, we simply have to apply the routing algorithm of our choice to route the traffic demand in this protected working capacity envelope. In our simulations, we route the lightpath requests based on the Dijkstra's algorithm [74] with cost of each link reciprocal to the free capacity of the span [60]. A lightpath request will be blocked if it cannot be routed in the protected working capacity envelope. As the same with Chapter 4,

In Chapter 4, we have presented three strategies for dynamic *p*-cycles design using the *ER*-based unity-*p*-cycle design heuristic [68], [69] for dynamic survivable WDM

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networks. In Chapter 4, Strategy-3 was always found to outperform the other two strategies. We have conducted simulations for the p -cycle-based PWCE design with different α . As in Chapter 4, we also use the metrics: blocking probability, redundancy and link utilization to evaluate the performance of the PWCE design and compare it with that of the dynamic p -cycle design using the *ER-based unity- p -cycle* heuristic and that of the FIR-SBPP (see details in Chapter 4). For the PWCE approach, the working path can only be set up in the PWCE. For the FIR-SBPP, the working path can be set up within the total capacities and not just in the PWCE. For each traffic load, we choose the first 10^5 lightpath requests as warm-up period, Fig. 5-4 shows the blocking probability for every 100000 lightpath requests after the first 10^5 lightpath requests for COST 239 network of when total traffic load is 253 (the traffic load per node is 23).

As demonstrated in Fig. 5-4, the blocking probability of each method is almost fixed at one value; the relative variation of blocking probability is less than 3%. Hence after the first 10^5 lightpath requests, the network has already arrived the stable state. The following performance comparisons are based on the average results after the first 10^5 lightpath requests.

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Figure 5-4 Blocking probability vs. number of arrived lightpath requests

Fig. 5-5 compares these three design approaches based on their blocking probability performance versus offered traffic load per node. As shown in Fig. 5-5(a), for the COST 239 network, when $\alpha = 2$, the *p*-cycle-based PWCE approach achieves virtually the same blocking probability as the dynamic *p*-cycle design (strategy-3) and the FIR-SBPP. As expected, the block probability increases as the traffic load increases. Fig. 5-5(a) also shows the impact of α on the blocking probability. The blocking probability at $\alpha = 2$ is the lowest for this network. Similar results are observed in Fig. 5-5 (b) for the NSFNET network where the lowest blocking probability under the PWCE design is achieved at $\alpha=5$. Therefore, the choice of α not only affects the total protected working capacity but also the blocking performance. We find that at $\alpha = 2$ for COST 239 and at $\alpha = 5$ for NSFNET, the maximal total protected working capacity can be

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obtained with the smallest blocking probability, indicating these as the best choice for α .

Fig. 5-6 shows the redundancy versus offered traffic load per node for different approaches for the COST239 and NSFNET networks, respectively. Fig. 5-6(a) clearly demonstrates the impact of α on the redundancy. The redundancy at $\alpha = 2$ is the lowest for the COST 239 network. Similar results are observed in Fig. 5-5 (b) for the NSFNET network where the lowest redundancy under the PWCE design is achieved at $\alpha = 5$. Therefore, the choice of α not only affects the total protected working capacity but also the redundancy performance. We find that at $\alpha = 2$ for COST 239 and at $\alpha = 5$ for NSFNET, we can obtain the maximal total protected working capacity with the lowest redundancy indicating these as the best choice for α . As shown in Fig. 5-6, when traffic load is relatively light (less than 24 Erlangs for COST 239 and 6 Erlangs for NSFNET), the p -cycle-based PWCE approach (with the best choice of α) has a slightly higher redundancy than the dynamic p -cycle design (strategy-3). However, when traffic load is relatively high, the p -cycle-based PWCE approach (with the best choice of α) has a slightly lower redundancy than the dynamic p -cycle design (strategy-3). This is because for the p -cycle-based PWCE approach, the spare capacity is pre-assigned to each edge and the total number of spare units is fixed, hence it has higher redundancy when the traffic load is relatively light.

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(a) Test network COST239

(b) Test network NSFNET

Figure 5-5 Blocking probability comparisons for the two test networks

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(a) Test network COST239

(b) Test network NSFNET

Figure 5-6 Redundancy comparisons for the two test networks

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Figure 5-7 Comparison of link utilization for the COST 239 Network

Figure 5-8 Comparison of link utilization for the NSF Network

In Figs. 5-7 and 5-8, the link utilization is plotted as the function of the arrived traffic load per node for the COST239 and NSFNET networks, respectively. These Figs.

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clearly demonstrate the impact of α on the link utilization. The link utilization at $\alpha = 2$ is the lowest for the COST 239 network. Similar results are observed in Fig. 5-8 for the NSFNET network where the lowest link utilization under the PWCE design is achieved at $\alpha = 5$. Therefore, the choice of α not only affects the total protected working capacity but also the link utilization performance. We find that at $\alpha = 2$ for COST 239 and at $\alpha = 5$ for NSFNET, we can obtain the maximal total protected working capacity with the lowest link utilization indicating these as the best choice for α .

5.5 Computational Complexity

We next compare the computational complexity for different schemes. For each lightpath request, the computational complexity of the p -cycle-based PWCE design for dynamic traffic is only the complexity of the routing algorithm. Since it has only one on-line processing step, in our simulations, it is proportional to $O(N^2)$ where N is the number of nodes in the network. The computational complexity of the ILP can be neglected, since the calculation for the ILP only needs to be performed once and is done offline. For each lightpath request, the computational complexity of the FIR-SBPP and the dynamic p -cycle design (Strategy-3) are $O(N^2) + O(E^2)$ and $O(N^2) + p \times O(W \times E \times M) + (1 - p) \times O(N \times M)$ respectively, where E is the number of edges, W is the number of wavelength channels per fiber and M is the number of candidate cycles, p is the probability of employing Strategy-1 to configure p -cycles (see details in Chapter 4). Typically, these would be much higher than the $O(N^2)$ complexity of the p -cycle-based PWCE design.

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For every successful lightpath in our simulation for test network COST239, the average computational time is approximately 0.02ms for p -cycle-based PWCE, 8 ms for Strategy-3 of the dynamic p -cycle design using the *ER-based unity- p -cycle* heuristic and 0.1ms for the FIR-SBPP approach. Note that the computing platform used is Intel Pentium IV 2.4GHz PC running Windows 2000 with 512 MB memory and 40GB hard disk. After a link failure, the FIR-SBPP needs a complex signaling process to inform multiple relevant nodes of failed primary lightpaths so that they can be switched to the backup lightpaths. Therefore, it needs longer restoration times (typically 150-300ms [93], [94]). For the p -cycle-based PWCE design and dynamic p -cycle design, both based on the p -cycle scheme, only the two end-nodes of the failed link will need to take action on failure. Therefore, both can achieve fast restoration (typically 30-80ms [93], [94]).

5.6 Conclusions

We have considered here the problem of dynamically survivable WDM networks and have presented the p -cycle-based PWCE approach for their design. We have developed a modified ILP formulation to determine the protected working capacity envelope and carried out computer simulations to evaluate the blocking performance and the redundancy performance with different maximum variations of w_j . The simulation results show that the choice of the maximum variations of w_j not only affects the total protected working capacity but also the blocking and redundancy performance. With the best choice of the maximum variations of w_j , the p -cycle-based PWCE design considered here achieves virtually the same blocking probabilities as

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the Strategy-3 of dynamic p -cycle design in Chapter 4 and the FIR-SBPP in spite of its substantially lower computational complexity.

Chapter 6 Shared P -Cycles Design for Survivable WDM Networks

6.1 Introduction

In this chapter, we propose a new approach, namely shared preconfigured protection cycles (shared p -cycles), for design of survivable WDM networks. The idea of the shared p -cycle design is that it allows multiple p -cycles that traverse a common span to share the spare capacity on that span so as to reduce the total spare capacity reserved for protection. We also develop an integer linear program (ILP) formulation to solve the problem of shared- p -cycles design for WDM networks with and without wavelength conversion. Numerical results show that the shared- p -cycles design is more efficient in the use of spare capacity and requires much less spare capacity than the conventional p -cycles design. To evaluate the redundancy performance of the shared p -cycle design method, a number of networks are tested under two different traffic patterns, namely distributed traffic pattern and centralized traffic pattern. Compared with the conventional p -cycle design, the shared p -cycle method can significantly reduce the redundancy by as much as 30% or more, and is most effective when the number of spans (nodes) allowed in the p -cycles is relatively small (half or

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less than half of the number of nodes in the network). In practice, the number of spans allowed in the *p*-cycles should be limited to a certain value such that the protection lightpath is not too long so as to meet the noise requirement of the transmission system.

6.2 Concept of Shared *p*-Cycles Design

The approach of the shared *p*-cycles design uses the basic principle of the conventional *p*-cycles design method, but it allows multiple candidate *p*-cycles that have a common span to share the spare capacity on that span and hence is more efficient in the use of spare capacity. Fig. 6-1(a) shows an example of a small network, where the label on each span is the number of working units on each span. Fig. 6-1 (b-d) shows three *p*-cycles (i.e, cycles 1:1-2-3-5-1, 2:3-5-4-3 and 3:2-3-5-2) that are selected for protection and have a common span 3-5. In the conventional *p*-cycles design [54], [56], [60]-[64], each of these three *p*-cycles will be assigned certain units of spare capacity, says n_i for the i th *p*-cycle. (Here we can simple get $n_1 = 2, n_2 = n_3 = 1$). Then, the total number of spare units reserved on span 3-5 for the purpose of protection is the sum of all the spare units needed for each of the three *p*-cycles (i.e., $\sum_{i=1}^3 n_i = 4$, as described in [54], [60]). With the shared *p*-cycles design method, the number of spare units reserved on the span 3-5 for protection will be smaller than $\sum_{i=1}^4 n_i$, as the spare units on span 3-5 will be shared by these four selected *p*-cycles. In the shared-*p*-cycle design method, the calculation of spare capacity reserved on the span 3-5 is not that simple. In this thesis, we focus on single span failure, so we can divide the full protection scenario into each single failure

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scenarios. We can clearly find out the relation of each single span and its protection *p*-cycles, as shown in table 6-1.

Figure 6-1 An example showing 4 *p*-cycles sharing a common span 3-5.

Table 6-1 the spans protected by *p*-cycles 1-3

Span	Protection <i>p</i> -cycles (units)	Spare units required on span 3-5
1-2	1(2)	2
2-3	1(2)	2
3-4	2(1)	2
4-5	2(1)	2
5-1	1(2)	2
2-5	1(2), 3(1)	3
3-5	1(2)	0
1-3	1(2)	2

From table 6-1, it is clearly seen that the total number of spare units required on span 3-5 is 3, which is smaller than $\sum_{i=1}^3 n_i = 4$. The reason is that cycle 1 and cycle 2 cannot provide protection for same span, cycle 2 and 3 can't either, so cycle 2,3 and cycle 1,2 can share spare units on span 3-5. Therefore, we can anticipate that the shared-*p*-cycles design can achieve better efficiency than the conventional *p*-cycles design.

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6.3 ILP Formulation of Shared p -Cycles Design

We present here an ILP formulation to solve the shared p -cycle design problem. The formulation determines a collection of p -cycles to be selected. The objective is to minimize the total spare capacity required while protecting all working traffic against any single span failure.

We model the WDM network as a graph $G(V, E)$ where V represents the set of WDM nodes and E is the set of edges. In the rest of this chapter, the terms of span and edge are used interchangeably. For a set of X , we use $|X|$ to denote the number of elements in the set. Without loss of generality, we assume that the traffic demand (in terms of number of lightpaths) between any two nodes is bidirectional, and identical in each direction, i.e., if the traffic demand from node i to node j is S lightpaths and then the traffic demand from j to i is also S lightpaths. This implies that all spans are bidirectional with equal capacity in each direction. A unit of capacity on an edge is defined as a bidirectional wavelength channel (i.e., one wavelength in each direction). For the sake of simplicity, we assume that the cost of a unit of capacity on every edge is identical. Assuming that edge j contains l_j fibers of K wavelengths in each direction, then the number of bidirectional channels on edge j is $c_j = l_j \times K$. Let P denotes the set of all possible candidate p -cycles for a given network topology. Note that the set of all possible candidate p -cycles can be pre-determined by the method reported in [72], and that, in practice, the selection of candidate p -cycles is usually subject to some constraints such as the maximum cycle length or span count [60], [68], [69].

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Since the formulation of the p -cycle design problem depends on whether WDM networks are capable of wavelength translation or not, we consider two types of networks, namely virtual wavelength path (VWP) networks and wavelength path (WP) networks [91], [92]. VWP networks, every optical crossconnect (OXC) node can convert a wavelength on any input fiber to any other wavelength on any output fiber and hence the wavelength continuity of lightpaths is not required; whereas no wavelength conversion can be performed at any OXC node in WP networks and hence the wavelength continuity of lightpaths is required [91].

6.3.1 Case 1 - VWP Networks

In order to formulate the shared p -cycles design problem for VWP networks, we define the following variables, as in [54], [60]:

$p_{i,j}$ indicates if span j is an on-cycle span of p -cycle i or not; $p_{i,j}$ is 1 if span j is an on-cycle span of p -cycle i , and 0 otherwise.

$x_{i,r}$ represents the number of backup paths that p -cycle i with one unit capacity can provide for the failed span r ; $x_{i,r}$ is 1 if the failed span r is an on-cycle span of p -cycle i , 2 if the failed edge r is a straddling span of p -cycle i , and 0 otherwise.

w_j and s_j are the number of working and spare units on span j , respectively.

In addition to the above variables, we also introduce two new variables:

$s_{j,r}$ is the number of spare units required to be reserved on span j to protect the working units of span r should span r fail

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$n_{i,r}$ is the number of spare units required on p -cycle i to protect the working units of span r should span r fail

In the conventional p -cycles design, the ILP formulas [54], [60] tried to calculate the amount of spare units required for all candidate p -cycles when any span fails. Then the amount of spare units required for span j is the sum of the spare units of those selected p -cycles that traverse span j . In our new ILP formulation for the shared p -cycles design, we first try to find the amount of spare units required on a specific span j when any span r other than span j fails, i.e. we try to calculate $s_{j,r}$ first. After finding all the $s_{j,r}$'s, we can then obtain the amount of spare units needed on span j , which should be the maximum value among all the $s_{j,r}$'s, i.e. $s_j = \max\{s_{j,r}\}$.

The shared p -cycles design problem can be formulated as follows:

$$\text{Objective:} \quad \min \sum_{j=1}^{|E|} s_j \quad (6-1)$$

$$\text{Constraints:} \quad s_{j,r} = \sum_{i=1}^{|P|} p_{i,j} n_{i,r} \quad \forall j, r \in E \text{ and } r \neq j \quad (6-2)$$

$$s_j = \max\{s_{j,r}\} \quad \forall j, r \in E \text{ and } r \neq j \quad (6-3)$$

$$w_j \leq \sum_{i=1}^{|P|} x_{i,j} n_{i,j} \quad \forall j \in E \quad (6-4)$$

$$w_j + s_j \leq c_j \quad \forall j \in E \quad (6-5)$$

All the variables in (6-1)-(6-5) are positive integers. The details for (6-1)-(6-5) are explained below. For a given network topology and traffic demand together with certain routing algorithm (e.g. shortest path), the values of $p_{i,j}$, $x_{i,r}$, w_j , and the sets of

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P and E can be pre-determined. Therefore, the task of (6-1)-(6-5) is to determine the optimal values of $n_{i,r}$, $s_{j,r}$ and s_j such that the summation of s_j 's in (6-1) is minimized. In the following discussion, we say two spans are *relevant* to each other if they are related with a p -cycle, i.e., they are either on-cycle or straddling spans of that p -cycle. We also say a span is relevant to a p -cycle if it is an on-cycle or straddling span of that p -cycle. Equation (6-2) determines the amount of spare units that need to be reserved on span j so as to protect the working units on span r ($r \neq j$) should span r fail. Note that, as reflected in the term $p_{i,j} n_{i,r}$ in (6-2), both spans j and r are relevant to p -cycle i . More specifically, span r is either an on-cycle span or a straddling span of p -cycle i , while span j is an on-cycle span of p -cycle i . The value of $p_{i,j} n_{i,r}$ represents the amount of spare units that are needed from p -cycle i should span r fail. It may also be noted that the number of working units of span r can be protected by p -cycle i should span r fail is determined by $x_{i,r} n_{i,r}$, where $x_{i,r}$ is 1 if span r is an on-cycle span, 2 if span r is a straddling span, and 0 otherwise. Since span r can be either an on-cycle or straddling span of many p -cycles, the right side in (2) takes into account all possible p -cycles. Equation (6-3) states that the amount of spare units required to be reserved on span j should take the maximum value among all the $s_{j,r}$'s, where $r \in E$ and $r \neq j$ (i.e., $\max\{s_{j,r}\}$). The constraint in (6-4) ensures that all working units on span j can be protected jointly by all relevant p -cycles if any span j fails. The constraint in (6-5) shows the capacity restriction on every span.

6.3.2 Case 2 – WP Networks

For the case of WP networks, we need to consider individual wavelengths on every span, since a lightpath between any two nodes may pass through a few spans and the

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wavelength assigned to that lightpath along the path must be the same [91]. Each span on one p -cycle also must be assigned the same wavelength with the corresponding failed working lightpath. And each p -cycle can only provide protection for the lightpath which has assigned the same wavelength with itself. This wavelength continuity constraint makes the problem more complicated. To facilitate the analysis, we can consider a WP network as K independent networks each with a different wavelength, where K is the number of wavelengths per fiber. Therefore, associated with each wavelength k , the shared p -cycles design problem can be formulated as follows.

$$\text{Objective:} \quad \sum_{j=1}^{|E|} \sum_{k=1}^{|K|} s_j(k) \quad (6-6)$$

$$\text{Constraints:} \quad s_{j,r}(k) = \sum_{i=1}^{|P|} p_{i,j} n_{i,r}(k) \quad \forall j, r \in E \text{ and } r \neq j \quad (6-7)$$

$$s_j(k) = \max\{s_{j,r}(k)\} \quad \forall j, r \in E \text{ and } r \neq j \quad (6-8)$$

$$w_j(k) \leq \sum_{i=1}^{|P|} x_{i,j} n_{i,j}(k) \quad \forall j \in E \quad (6-9)$$

$$w_j(k) + s_j(k) \leq l_j \quad \forall j \in E \quad (6-10)$$

The variables in (6-6)-(6-10) have the similar meanings as those in (6-1)-(6-5) except that each of them is a function of wavelength, k , e.g., $w_j(k)$ and $s_j(k)$ represent the number of working units and the number of spare units at wavelength k on span j . The objective in (6-6) and constraints in (6-7)-(6-10) have the same meanings as the objective in (6-1) and constraints in (6-2)-(6-5), respectively, but the constraints in (6-7)-(6-10) are each associated with a specific wavelength, k . Therefore, the shared p -

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cycles design problem in WP networks can be solved for each wavelength independently.

6.4 Simulation Studies

To evaluate the effectiveness of the shared p -cycles design method, we have selected the pan-European COST 239 network [75], [76] and three other networks reported in [64] as the test cases. These test networks have different numbers of nodes and spans. Their topologies are shown in Fig. 3-3. The software CPLEX8.0 [100] is used to get the optimal solution based on the ILP formulation presented in Section 6.1 and 6.3. Here, we restrict our discussions to VWP networks. Without loss of generality, we assume that in all four test networks, every span has two optical fibers transmitting in opposite directions and every fiber can carry up to 64 wavelength channels. We also assume the traffic demand between any two nodes is bi-directional and identical in each direction. As the same with Chapter 3, we consider two traffic patterns [69]: (i) distributed pattern where the number of lightpath requests between any two nodes is selected from 0 to S (both inclusive) using a uniform random distribution; (ii) centralized pattern where each node has lightpath demands from and to a central node only and the number of lightpaths between the central node and any other node is a uniformly distributed random integer between 0 and S (both inclusive). In order to balance the traffic load on all the spans and minimize the number of working wavelengths on each span, The lightpath requests are routed based on Dijkstra's algorithm [74], and the 'length' of each bidirectional edge is reciprocal to the free capacity of the span [60].

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In optical transparent networks where regeneration of optical signals is not possible or difficult to realize, it is necessary to keep the hop (span) count (or the distance) of optical paths within a certain limit so as to maintain good signal quality. This is because optical signals are inevitably impaired by linear or nonlinear optical effects such as crosstalk, amplified spontaneous emission (ASE), chromatic dispersion, self-phase and cross-phase modulations, etc., when they traverse optical links and OXC nodes along the paths. Therefore, from the viewpoint of signal quality, it is also important to keep the span count (or physical length) of selected *p*-cycles within a certain limit, so that the backup paths for protection can also meet the requirement of satisfactory signal quality. As in [60], [69], in the following we consider the impact of the maximum number of spans allowed in the *p*-cycles on the redundancy performance. Note that the number of nodes in a *p*-cycle is equal to the number of spans in that *p*-cycle. We denote N_{span} as the maximum number of spans (nodes) allowed in the *p*-cycles.

Table 6-2 Difference of Redundancy for COST239 network

Distributed traffic pattern							
N_{span}	5	6	7	8	9	10	11
Diff	0.32	0.23	0.15	0.10	0.06	0.031	0.007
95% CI	0.30	0.21	0.13	0.072	0.032	0.011	0.0041
	~	~	~	~	~	~	~
	0.34	0.25	0.17	0.14	0.10	0.053	0.012
Centralized traffic pattern							
N_{span}	5	6	7	8	9	10	11
Diff	0.32	0.27	0.19	0.12	0.06	0.027	0.005
95% CI	0.30	0.24	0.16	0.10	0.032	0.011	0.0021
	~	~	~	~	~	~	~
	0.34	0.31	0.22	0.15	0.10	0.052	0.0083

Table 6-3 Difference of Redundancy for test network 2

Distributed traffic pattern

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N_{span}	4	5	6	7	8	9	10	11
Diff	0.34	0.26	0.22	0.18	0.12	0.10	0.09	0.09
95% CI	0.30	0.21	0.17	0.12	0.08	0.06	0.04	0.04
	~	~	~	~	~	~	~	~
	0.39	0.30	0.27	0.24	0.15	0.16	0.13	0.13
Centralized traffic pattern								
N_{span}	4	5	6	7	8	9	10	11
Diff	0.40	0.30	0.16	0.12	0.063	0.044	0.019	0.019
95% CI	0.35	0.26	0.11	0.081	0.041	0.024	0.014	0.013
	~	~	~	~	~	~	~	~
	0.46	0.35	0.20	0.16	0.082	0.064	0.25	0.26

Table 6-4 Difference of Redundancy for test network 3

Distributed traffic pattern										
N_{span}	6	7	8	9	10	11	12	13	14	15
Diff	0.094	0.10	0.068	0.045	0.030	0.020	0.014	0.013	0.013	0.013
95% CI	0.064	0.061	0.044	0.031	0.021	0.014	0.011	0.010	0.010	0.010
	~	~	~	~	~	~	~	~	~	~
	0.126	0.14	0.089	0.054	0.042	0.27	0.017	0.016	0.016	0.016
Centralized traffic pattern										
N_{span}	6	7	8	9	10	11	12	13	14	15
Diff	0.18	0.13	0.12	0.088	0.076	0.056	0.044	0.040	0.040	0.040
95% CI	0.12	0.10	0.091	0.062	0.051	0.021	0.025	0.020	0.020	0.020
	~	~	~	~	~	~	~	~	~	~
	0.24	0.16	0.15	0.11	0.10	0.084	0.061	0.060	0.060	0.060

Table 6-5 Difference of Redundancy for test network 4

Distributed traffic pattern											
N_{span}	5 ~ 6	7 ~ 8	9	10	11	12	13	14	15	16	17 ~ 19
Diff	0.11	0.10	0.086	0.065	0.051	0.038	0.028	0.017	0.013	0.011	0.009
95% CI	0.09	0.08	0.06	0.05	0.03	0.02	0.01	0.011	0.010	0.008	0.006
	~	~	~	~	~	~	~	~	~	~	~
	0.13	0.12	0.11	0.08	0.08	0.06	0.05	0.023	0.016	0.015	0.012
Centralized traffic pattern											
N_{span}	5 ~ 6	7 ~ 8	9	10	11	12	13	14	15	16	17 ~ 19
Diff	0.27	0.16	0.14	0.12	0.11	0.094	0.087	0.082	0.073	0.066	0.052
95% CI	0.24	0.12	0.10	0.08	0.07	0.072	0.065	0.061	0.052	0.043	0.04
	~	~	~	~	~	~	~	~	~	~	~
	0.30	0.20	0.18	0.14	0.13	0.11	0.10	0.010	0.094	0.078	0.06

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For each test case, we generate 10^3 lightpath requests matrices. Here we firstly calculate the total working capacity of each demand matrix and then use software CPLEX 8.0 to calculate the total spare capacity achieved by our ILP model for shared p -cycles design and ILP model for conventional p -cycles design, respectively. We are mostly interested to find out the difference of the redundancy between these two methods. Tables 6-2 to 6-5 demonstrate the difference (Diff) of redundancy between these two methods. 95% CI is the 95% confidence interval for the difference of redundancy. The total capacity on each span is $c_j = 64$. The average number of lightpaths between any two nodes is 5 for the distributed traffic pattern, and the average number of lightpaths between a central node and any other node is also 5 for the centralized traffic pattern (in our simulation the central node is node 1). The redundancy in these two figures is the ratio of the sum of spare units required over all spans to the sum of working units over all spans, i.e., $\sum_{j \in E} s_j / \sum_{j \in E} w_j$. Figs. 6-2 to 6-5 show the average redundancy comparison between the shared p -cycles design and the conventional p -cycles design for various values of N_{span} for the distributed and centralized traffic patterns, respectively.

From these performance comparisons, we can draw the following results:

- (i) The shared p -cycles design requires much lower redundancy than the conventional unshared p -cycles design, regardless of traffic patterns, particularly when N_{span} is relatively small (about half or smaller than half of the number of nodes in the network).
- (ii) The redundancy is significantly reduced for both design methods as N_{span} increases.

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- (iii) The redundancy for the shared p -cycles design drops very fast when N_{span} is increased from a small value, but it remains almost unchanged when N_{span} exceeds a certain value (denoted as threshold value). The threshold values are approximately 6, 6, 8 and 9 for the test networks 1, 2, 3 and 4, respectively.
- (iv) The result in (ii) also means that if the hop count of backup paths is limited to smaller values so as to meet the requirement of satisfactory signal quality, the shared p -cycle design is more effective than the conventional unshared p -cycle design. For the example of test network 1 in Fig. 6-2 (a), the redundancy is 65% for the conventional unshared p -cycles design, and 33% for the shared p -cycles design when N_{span} is 5. In this instance, the redundancy for the shared p -cycles design is only half of that for the unshared p -cycles design.
- (v) The difference in the redundancy between both design methods becomes smaller or disappears as N_{span} approaches the number of nodes in the network.

The above results can be explained as follows. When N_{span} is small, the selected p -cycles are small in size and tend to have more common spans but fewer straddling spans, and hence the shared p -cycle design requires much lower redundancy than the conventional unshared p -cycle design. As N_{span} increases and approaches to the number of nodes in the network, both the design methods tend to select bigger p -cycles with more straddling spans (but fewer common spans) rather than smaller p -cycles with fewer straddling spans (but more common spans), and hence the redundancy for either method is significantly reduced, and also the difference in the redundancy between them becomes smaller or disappears.

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 6-2 Redundancy comparison between the shared *p*-cycles design and the conventional unshared *p*-cycles design for test network COST239

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 6-3 Redundancy comparison between the shared *p*-cycles design and the conventional unshared *p*-cycles design for test network 2

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 6-4 Redundancy comparison between the shared *p*-cycles design and the conventional unshared *p*-cycles design for test network 3

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(a) Distributed traffic pattern

(b) Centralized traffic pattern

Figure 6-5 Redundancy comparison between the shared *p*-cycles design and the conventional unshared *p*-cycles design for test network 4

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(a) Test network 1 (COST239)

(b) Test network 2

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(c) Test network3

(d) Test network 4

Figure 6-6 Redundancy versus the average number of lightpaths between any two nodes for distributed traffic pattern

We have also examined the redundancy of the shared *p*-cycles design under various average number of lightpaths between any two nodes for the distributed traffic pattern.

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Fig. 6-6 demonstrate the redundancy versus average number of lightpaths between any two nodes for the distributed traffic pattern, where N_{span} is 6 for test network 1, 6 for test network 2, 8 for test network 3, and 9 for test network 4. Fig. 6-6 clearly demonstrates that the shared p -cycles design always achieves lower redundancy than the conventional unshared p -cycles design, and the redundancy is reduced as the average traffic load increases.

6.5 Computational Complexity of Shared p -Cycles Design

Compared with the conventional unshared p -cycles design, the shared p -cycles design is attractive since it requires much less spare capacity, particularly when the hop count allowed in p -cycles is about half or smaller than half of the number of nodes in the network. However, we should mention that this is achieved at the expense of higher computational complexity and more complicated operation. For a network with a set of spans, E , the computational complexity of shared p -cycles design is approximately $|E|$ times higher than that of the conventional unshared p -cycle design, since there are $|E|$ variables (i.e., $n_{i,r}, \forall r \in E$) associated with every p -cycle i , and also $|E|$ variables (i.e., $s_{j,r}, \forall r \in E$) associated with every span j . For the purpose of network planning, the computation is usually carried out off-line, hence it would not be a big problem. Table 6-2 compares the computational time of the conventional unshared p -cycles design and the shared p -cycles design for the four test network. Note that the computing platform used is Intel Pentium IV 2.4-GHz PC running Windows 2000 with 512-MB memory and 24-GB hard disk. The average number of lightpaths between any

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two nodes is 5. From table 6-6, we can clear see that the computational time of shared *p*-cycles design is much longer than unshared *p*-cycles design.

Table 6-6 Computational time comparisons for different networks

Test Network			Test Network1	Test Network2	Test Network 3	Test Network 4
Number of nodes			11	11	15	19
Number of edges			52	40	56	78
Average node degree			4.7	3.6364	3.733	4.1053
N_{span}			6	6	8	9
Computational time (s)	Distributed pattern	unshared <i>p</i> -cycles design	55.1	2.3	18.7	202.4
		shared <i>p</i> -cycles design	812.5	45.2	325.8	4802.4
	Centralized pattern	unshared <i>p</i> -cycles design	52.1	2.1	18.2	201.4
		shared <i>p</i> -cycles design	806.8	42.2	316.2	4621.3

6.6 Summary

In this chapter, we presented a new shared *p*-cycles design method to improve the efficiency in the use of spare capacity for survivable WDM optical networks. We have developed an ILP formulation to solve the shared *p*-cycles design problem for both VWP and WP networks. To compare with the conventional unshared *p*-cycles design, we have numerically examined four different test networks. Our investigations have shown that, compared with the conventional unshared *p*-cycles design, the shared *p*-cycles design is most effective when the maximum number of spans (or nodes)

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allowed in the p -cycles is relatively small (i.e., half or less than half of the number of nodes in the network). The difference in the redundancy between the two design methods becomes smaller or disappears as the maximum number of spans allowed in the p -cycles increases. The improved efficiency of the shared p -cycles design is at expense of more complicated operation and higher computational complexity.

Chapter 7 Conclusions

7.1 Conclusions

WDM optical networks carry very large volumes of traffic and failures in these networks will have catastrophic effects. It is therefore imperative that they should be able to survive an accidental failure such as a fiber cut or a node failure. In this thesis, we have investigated approaches for providing survivability features for WDM optical networks, and have discussed in particular the method of pre-configured protection cycle (p -cycle). This is primarily because the method of p -cycle can provide protection with ring-like fast speed and mesh-like high efficiency of spare resources. The p -cycle method makes use of the ring protection switching function (originally developed and used in SONET/SDH rings) to perform fast protection switching, but goes beyond the ring functionality. It can provide protection not only for on-cycle spans but also for straddling spans, and hence can achieve mesh-like high efficiency.

The problem of p -cycle design can be formulated with an integer linear program (ILP), which is very computationally intensive if the number of network nodes is large. In Chapter 3, we have proposed a heuristic algorithm, named *ER-based unity- p -cycle*

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design, as a sub-optimum solution for fast on-line computation. To evaluate the effectiveness of this new heuristic, we have studied four networks and compared the redundancies obtained by different methods under two different traffic patterns. The study has shown that this proposed heuristic performs very well for both distributed and centralized traffic patterns and that the redundancies obtained by the heuristic algorithm are very close to that of the optimal solution using the ILP but with much reduced computational time. To further improve the computation speed, modifications were done for the heuristic algorithm. Firstly, if there are several cycles with the same efficiency ratio, we always choose the cycle with the largest number of nodes. Secondly, we may choose multiple cycles with the best efficiency ratios simultaneously at a time so long as these cycles do not have a common span. The results obtained after the modifications are then compared with the results before the modifications.

In Chapter 4, we have considered the design problem of dynamically survivable WDM networks and extended the *ER-based unity- p -cycle design* heuristic proposed in this work to solve this problem. We have proposed three strategies to dynamically configure p -cycles that are adaptive to changing traffic demand. The blocking performance and redundancy performance for these strategies have been studied under two different traffic patterns for two different test networks by computer simulation. The results have shown that Strategy-3, which combines the advantages of both Strategy-1 and Strategy-2, achieves the best blocking and redundancy performance among the three strategies and that the average computational time required by it for handling a new lightpath is comparable to that of Strategy-2. Strategy-2 is the fastest but its blocking performance is much worse than that of Strategy-1 and Strategy-3

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because of the fact the existing p -cycles are allowed to be released. It has a much higher redundancy than other two strategies. Strategy-1 has a better blocking performance than Strategy-2 but it is the slowest in processing new lightpaths. The simulations also reveal that the blocking probability of Strategy-3 is the almost the same as that of the SBPP scheme, even though it has a much faster restoration speed than the SBPP. The computational complexity for different schemes is also discussed in Chapter 4. For each lightpath request, the computational complexity is $O(N^2) + O(W \times E \times M)$ for Strategy-1, $O(N^2) + O(E \times M)$ for Strategy-2 and $O(N^2) + p \times O(W \times E \times M) + (1 - p) \times O(N \times M)$ for Strategy-3, where N is the number of nodes, E is the number of edges, W is the number of wavelength channels per fiber and M is the number of candidate cycles, p is the probability of employing Strategy-1 to configure p -cycles. It is clear that the computational complexity of Strategy-1 is much higher than the other two strategies. This is because for Strategy-1, when a new lightpath arrives, all the existing p -cycles are freed up and then reconfigured to provide protection for all working units on each edge. On the other hand, Strategy-2 only configures certain p -cycles to provide protection for the working units on the edge which is traversed by the newly established lightpath. Hence Strategy-2 has the lowest computational complexity. Strategy-3 combines Strategy-1 and Strategy-2 so that its computational complexity depends on p (the probability of employing Strategy-1 to configure p -cycle). In our simulations, p is less than 10%. Hence the average computational complexity of Strategy-3 is close to that of Strategy-2.

In Chapter 5, we have presented the p -cycle-based PWCE approach to solve the problem of dynamically survivable WDM networks. We have developed a modified ILP formulation to determine the protected working capacity envelope and carried out

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computer simulations to evaluate the blocking performance and the redundancy performance with different maximum variations of w_j . The simulation results show that the choice of the maximum variations of w_j not only affects the total protected working capacity but also the blocking and redundancy performance. With the best choice of the maximum variations of w_j , the p -cycle-based PWCE design considered here achieves virtually the same blocking probabilities as those obtained with Strategy-3 of the dynamic p -cycle design presented in Chapter 4 and the FIR-SBPP approach, in spite of its substantially lower computational complexity.

In Chapter 6, a new approach called shared p -cycles design is proposed to improve the efficiency in the use of spare capacity for survivable WDM optical networks. We have developed an Integer Linear Programming (ILP) formulation to solve the shared p -cycle design problem for both VWP and WP networks. To compare with the conventional unshared p -cycles design, computer simulations have been conducted where four different test networks have been investigated. Our investigations have shown that, compared with the conventional unshared p -cycles design, the shared p -cycles design is most effective when the maximum number of spans (or nodes) allowed in the p -cycles is relatively small (i.e., half or less than half of the number of nodes in the network).

7.2 Suggestions for Future Works

Although, an intensive study on design of p -cycle-based static or dynamic survivable WDM network has been carried out in this thesis, there still exist some issues that

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would be interesting to consider. In this section, we present a number of possible extensions of the current work.

One possibility is to apply our proposed *ER-based unity-p-cycle design* heuristic to the design of survivable wavelength path (WP) networks. In WP networks, the nodes have no capabilities of wavelength conversion, and hence the sharing of protection capacity may only occur among connections of the same wavelength. We can jointly apply our *ER-based unity-p-cycle design* heuristic together with some wavelength assignment algorithm to solve such *p-cycle* design problem in WP networks for both static traffic and dynamically changing traffic.

In Chapter 4, we considered two dynamically changing traffic patterns, i.e., distributed traffic pattern and centralized traffic pattern. It would be interesting to study the blocking performance under a more generic traffic pattern. A network with N nodes has a total of $N(N-1)$ directional node pairs. We can use a $N \times N$ matrix to describe the traffic distribution. Let p_{ij} be the probability that a new lightpath request originates at node i and terminates at node j . When a new lightpath request arrives, we use a $N \times N$ probability matrix $P=[p_{ij}]$ to determine the source and the destination nodes. The p_{ij} is given by

$$p_{ij} = M_{ij} / S, \quad S = \sum_{i=1}^N \sum_{j=1}^N M_{ij}$$

where M_{ij} ($i \neq j$) is a random integer that is selected from 1 to L (both inclusive) using a uniform random distribution and L is an integer greater than 1. M_{ij} is set to be 0 for $i=j$, since a lightpath is not likely to be generated and terminated by the same node. It should be noted that a larger value of L implies that the traffic is more non-uniform.

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$L=1$ means that the traffic is uniformly distributed among the nodes. It would be interesting to evaluate the performance of our dynamic p -cycle design strategies under such a generic traffic pattern with dynamically arriving lightpath requests.

As shown in Chapter 5, the p -cycle-based PWCE performs well for the distributed traffic pattern. It would be interesting to study the p -cycle-based PWCE design under a dynamically changing traffic pattern, particularly, non-uniform traffic pattern. Under a dynamically changing traffic pattern, the designed PWCE also needs to be changed accordingly.

As in [60], we can extend the ILP formulation for the shared p -cycles design in Chapter 6 to the joint optimization of working and spare capacity problem so as to further reduce the spare capacity. To reduce computational complexity of the ILP model, heuristic algorithms are desirable for the shared p -cycles design.

APPENDIX I: ILP AND CPLEX

Appendix I: ILP and CPLEX

Linear programming (LP) [101] is a most widely used optimization technique designed to optimize the usage of limited resources in operation research. LP problems are characterized by objective functions and constraints. In LP, the objective function and constraints must be linear expressions. An expression is linear if it can be expressed in the form $c_1x_1 + c_2x_2 + \dots + c_nx_n$ where $c_1, c_2, \dots, c_n$ are constants. For example, $3x_1 + 5x_2 + 7x_3 + 19x_4$ is a linear expression; x^2 and $\sin x$ are not. Integer Linear Programming (ILP) is a specific case of LP in which all the variables must be integer variables. Here is a simple example of ILP problem:

Objective function:

$$\text{Maximize } z = 3x_1 + 2x_2$$

Constraints:

$$\text{Subject to: } 1. \ 2x_1 + x_2 \leq 100$$

$$2. \ x_1 + x_2 \leq 80 \quad x_1 \text{ and } x_2 \text{ are integer variables.}$$

In the thesis, we use CPLEX [100], a well-known tool for solving ILP problems. CPLEX is a product developed by ILOG. CPLEX Interactive Optimizer is a command-line utility provided with CPLEX. This utility serves as a prototyping and debugging tool for applications developed with CPLEX Component Libraries. By using CPLEX Interactive Optimizer, we can easily enter our ILP model to CPLEX and get the solution of our objective. Basic commands are listed below:

add	add constraints to the problem
baropt	solve using barrier algorithm
change	change the problem

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display	display problem, solution, or parameter settings
enter	enter a new problem
help	provide information on CPLEX commands
mipopt	solve a mixed integer program
netopt	solve the problem using network method
optimize	solve the problem
primopt	solve using the primal method
quit	leave CPLEX
read	read problem or basis information from a file
set	set parameters
tranopt	solve using the dual method
write	write problem or solution info. to a file
xecute	execute a command from the OS

For the above simple ILP example, we can easily enter the model and get the solution by using CPLEX Interactive Optimizer.

```
CPLEX> enter
Enter name for problem: an example
Enter new problem ['end' on a separate line terminates]:
Maximize
3x1+2x2
Subject to
2x1+x2 <=100
x1+x2 <=80
end
CPLEX> optimize
Tried aggregator 1 time.
No LP presolve or aggregator reductions.
Presolve time = 0.03 sec.
```

```
Iteration log . . .
Iteration: 1 Dual infeasibility = 0.500000
Iteration: 3 Dual objective = 180.000000
```

```
Dual - Optimal: Objective = 1.8000000000e+002
Solution time = 0.06 sec. Iterations = 3 (2)
To see the results, type display on the command prompt and it will show the options.
```

```
CPLEX> display
```

Display Options:

problem	display problem characteristics
sensitivity	display sensitivity analysis
settings	display parameter settings
solution	display existing solution

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```
CPLEX> display solution variables
Display values of which variable(s): -
Variable Name      Solution Value
x1                  20.000000
x2                  60.000000
```

(Note: - To see all variables, just press “ - ” and press enter.

```
CPLEX> display solution objective
Dual - Optimal: Objective = 1.8000000000e+002
```

Model information can be solved to file using command “write”. The model can be saved by using .lp extension files.

```
CPLEX> write mymodel.lp
```

Problem written to file 'mymodel.lp'.

The solution can be save by using .txt extension files.

```
CPLEX> write mymodel.txt
```

Solution written to file 'mymodel.txt'.

Model information can be loaded from the files using command “read”.

```
CPLEX> read mymodel.lp
```

Problem 'mymodel.lp' read.

Read time = 0.00 sec.

For large problems, we can write a small program in C/C++ which can read the data from the data files and write the model to a text file in the above-mentioned format. Then we must save the file with “.lp” extension. Finally we use CPLEX Interactive Optimizer to read the model from the file and solve it.

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AUTHOR'S PUBLICATIONS RELATED TO THIS THESIS

Author's Publications Related to This Thesis

1. Z. R. Zhang, W. D. Zhong and B. Mukherjee, "A heuristic algorithm for design of survivable WDM networks," *IEEE communications letters*, Vol.8, pp.467-469, July 2004 (related to Chapter 3).
2. W. D. Zhong and Z. R. Zhang, " p -cycles-based dynamic protection provisioning in optical WDM networks," *IEICE Trans. Commun.*, Vol. E88-B, May 2005, pp.1921-1926 (invited paper, related to Chapter 4).
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7. W. D. Zhong and Z.R. Zhang, "Design of survivable WDM network with shared- p -cycles," *Proceedings Optical Fiber Communications Conference (OFC 2004)*, Los Angeles, Feb. 22-27, 2004 (related to Chapter 6).

AUTHOR'S PUBLICATIONS RELATED TO THIS THESIS

8. W. D. Zhong and Z.R. Zhang, "Fast and dynamically pre-configured protection cycles for survivable WDM networks," *Proc. OECC/COIN 2004*, Yokohama, Japan, July 2004, pp.614-615. (Invited paper, related to Chapter 4).
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