STUDY OF *P*-CYCLE BASED PROTECTION IN OPTICAL NETWORKS AND REMOVAL OF ITS SHORTCOMINGS

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CERTIFICATE

It is certified that the work contained in the thesis entitled "*STUDY OF P-CYCLE BASED PROTECTION IN OPTICAL NETWORKS AND REMOVAL OF ITS SHORTCOMINGS*", by Rachna Asthana (nee Srivastava), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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SYNOPSIS

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Today's optical networks are carrying enormous traffic which is doubling almost every year. The traffic includes voice, video, data and various real time application services like remote monitoring and control, Remote Surgery etc.. The internet has become part of almost every home. The existence of the World Wide Web and Internet can be said to be built on optical long haul networks. The first generation of optical networks is using an optical transmission medium in the form of optical fibers as point-to-point links. Mostly SONET (Synchronous Optical Network) / SDH (Synchronous Digital Hierarchy) standard is used to deploy these networks. At each network node, traffic is subjected to O-E-O (Optical-Electrical-Optical) conversions. The nodes decide transmission bit rate, protocol and format i.e. they are opaque. The advancement in optical devices like optical multiplexers, optical cross-connects, erbium doped fiber amplifiers, wavelength converters, tunable transmitters and receivers etc., has eliminated the need of O-E-O conversions at each node and made way for the second generation of optical networks.

Various studies have shown that in these networks, the failure rate is of the order of one fiber cut in four days for a network with 30,000 route-miles of fiber, and a single fiber can carry more than 160 wavelengths using dense wavelength division multiplexing (DWDM) technique. The length of the laid optical fibers through out the world is in hundreds of million miles. Thus, the survivability of optical networks has become a necessity and it has created a lot of interest among the research community. As a result, many protection and restoration schemes for the survivability of optical networks have been reported in the literature.

The optical network protection schemes have to prove themselves on the basis of two main parameters, speed of restoration and capacity efficiency. Out of several path and span based protection techniques discussed in Chapter 3, *p*-cycles (pre-configured cycles) are one of the most promising techniques for shared span protection. The *p*-cycles are the pre-connected closed structures of the spare capacity of the network. The spare capacity is used to provide protection to the working paths. The working paths will be in the form of lightpaths in all optical networks. The *p*-cycle can protect all the on-cycle spans as well as straddling (chords) spans. They have combined the efficiency advantage of mesh networks with speed advantage of ring networks. The mesh like efficiency can be achieved due to the shared protection provided by the *p*-cycle to all the on-cycle spans as well as straddling spans. The spare capacity of the network is pre-connected to form the *p*-cycles. Hence, only two switching actions (as in rings) at the end nodes of the failed span, are needed in the event of failure to switch the traffic to the protection path provided by the pre-configured *p*-cycle. Hence, they qualify both the requirements; restoration speed and efficiency. They can provide complete solution against single failure in a network. However, there are some issues which are still to be addressed for enhancing the effectiveness of *p*-cycles. In the present work, these issues have been discussed and efforts have been made to resolve them without compromising on any of the features of *p*-cycles.

In any real network, *p*-cycles can be deployed with distributed cycle pre-configuration (DCPC) protocol. The DCPC protocol is the first of its kind to form the *p*-cycles in a real network in completely distributed manner. The *p*-cycles are searched and pre-configured in the spare capacity using DCPC protocol. However, with DCPC protocol, only one *p*-cycle can be found in one iteration even if multiple copies of the same *p*-cycle exist. Further, in case of optical *p*-cycle networks, *p*-cycles can be deployed at the wavelength level. If all the copies of the same *p*-cycle can be aggregated together then *p*-cycle can be deployed at waveband level resulting in reduction in the requirement of switching fabrics, switching complexities and simplified management issues. The working paths which are also at waveband level, can be switched collectively to the aggregated *p*-cycles in the event of failure. Thus, the DCPC protocol needs some modifications to improve its efficiency.

A lot has been said in the literature about the formation of *p*-cycles. However, there are various issues related with restoration after a failure event. One such issue is the length of the restored path. The capacity efficiency of *p*-cycles is because of shared span protection. The cost paid for the efficiency is in terms of long restored path lengths. There may be repetition of many nodes in the long restored paths. It will give rise to loop backs at these repeated nodes in the restored path. The restored path lengths can be shortened by removal of these loop backs. Further, the length of these loop backs depends upon the fact that which *p*-cycle is being used to protect which particular path. The reliability of *p*-cycles is also a matter of concern. They have inferior reliabilities as compared to other schemes mainly due to long restored paths length.

All the traffic on every span of the network can be provided protection against single failure with *p*-cycles. However in any network, there are some low availability spans which need special protection techniques. The networks also carry some critical traffic (e.g. Remote Surgery) which again needs special protection.

To investigate the above mentioned problems, the present work has been carried out with the following objectives.

- To modify the distributed protocol for the formation of *p*-cycles such that its computational complexity can be reduced and the advantages of waveband switching can be incorporated [Section 5.2.2, pp. 96-100].
- To reduce the restored path lengths without compromising on any features of the *p*-cycles with second phase reconfiguration technique [Section 6.2, pp. 106-109].
- To develop a distributed protocol for removal of loop backs, so that it can be implemented in a network designed with *p*-cycle based protection [Section 7.1, pp. 151-156].
- To formulate and solve the problem of optimum allocation of *p*-cycles [Section 7.2, pp. 156-159].
- To develop mathematical formulation of restored path lengths in terms of number of nodes in the network [Sections 6.3, and 6.4 pp. 109-115].
- To develop a model and study the effect of removal of loop backs on the reliability of *p*-cycles [Section 6.2, pp. 191-198].
- To develop specialized protection techniques for survivability with low availability spans, and for critical traffic through the network [Chapter 8, pp. 201-224].

The work done has been organized in Chapters 1 through 9 in the present thesis.

We begin with an introduction to the evolution of second generation of optical networks in Chapter 1. The importance of survivability for the success of second generation of optical networks, the motivation behind the work done in the present thesis, has also been highlighted in the chapter.

In Chapter 2, we present the concepts of graph theory, reliability and some mathematical operations used throughout the thesis to explain and evaluate the schemes developed in the present work.

The review of various protection and restoration techniques used in optical networks has been presented in Chapter 3. The most promising technique of span protection, *p*-cycles, has been studied and reviewed in depth in Chapter 4. Various formation methods of *p*-cycles, the capacity efficiency, the types of protection and the method of its implementation have been studied and presented in the chapter.

In Chapter 5, we have given the test networks and the simulation conditions which have been used throughout the thesis. The DCPC protocol with score and numpath metric has been studied with various spare capacities provisioned in the network. The modifications in the DCPC protocol are proposed and the effects of modified DCPC on computational complexities, number of *p*-cycles and switching fabrics have been presented.

The concept of loop backs and mathematical model for its removal have been given in Chapter 6. The relationships between the restored path lengths before and after removal of loop backs and the number of nodes in the network for average nodal degree of two, have been derived in this chapter. The performance of removal of loop back with respect to restored path lengths has been evaluated with various methods of *p*-cycle formation, average nodal degree, number of nodes in the network, and traffic distributions. The released capacity during removal of loop backs can be used for protection against second failure. The effect of released capacity on dual failure survivability has also been evaluated.

In Chapter 7, the distributed protocol for removal of loop backs has been developed for implementation in the optical network designed with *p*-cycles based protection. The effect of *p*-cycle allocation to the paths passing through the failed span has been discussed. Further, the optimum *p*-cycle allocation problem has been formulated and its solution using Hungarian algorithm has been presented. The improvements due to optimum path allocation on restored path lengths have been shown. The models for reliability analysis of paths without removal of loop backs and with removal of loop backs have been developed and the reliability improvements have been presented.

The specialized protection techniques based on dedicated *p*-cycles, for low availability spans and for critical traffic through the network, have been presented and evaluated with respect to spare capacity requirement, in Chapter 8.

Finally, conclusions, scope for future work and summary of contributions of the present thesis have been given in Chapter 9.

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Rachna Asthana (nee Srivastava)

Dedicated

To

My Parent-In-Laws

and

My Parents

Table of Contents

List of Figures

List of Tables

List of Symbols

[ ]	Ordered set of nodes.
[R]	Nodes of the working path from source to destination.
[F]	The failed span (F_1, the upstream node, and F_2, the downstream node).
[C]	The *p*-cycle with the nodes organized in such a way that F_1 is the first node and F_2 is the last node in [C].
[O]	The portion of the working path from source node to the upstream node of the failed link.
[D]	The portion of the working path from downstream node of the failed link to the destination node.
[FP]	The restored path before RLB.
[FR]	The restored path after RLB.
W_i	Set of working paths passing through failed span *i* indexed by *r*.
S	Set of spans, indexed by j .
P	Set of *p*-cycles indexed by p .
P_1	Set of all the *p*-cycles of the network indexed by *p* excluding the elements of P_3.
P_2	Set of *p*-cycles indexed by p_{spk}. The p_{spk} is the smallest *p*-cycle used for protection of low availability span *k*. The number of *p*-cycles in P_2 is equal to the number of LAS in the network.
P_3	Set of *p*-cycles passing through at least one member of CS.
D	Set of demand pairs having non zero demand indexed by t .
E^t	Set of eligible working routes for demand pair t , indexed by e .

L_U The length of [U]; defined as the total number of nodes in the set minus one.

L(X) The length of the loop back at node X.

J_{UX} Index of node X in the set [U]. The index starts from 0 and ends at L_U.

L_{WRLB} The average length of the restored paths without RLB.

L_{RLB} The average length of the restored paths with RLB.

T_{sp} Total spare capacity required for the formation of *p*-cycles.

c_j Cost of span j (assumed to be one throughout in the present work).

w_j Working capacity on span j .

π_j^p Equal to 1 if *p*-cycle p crosses span j , 0 otherwise.

x_j^p Equal to 1 if the cycle p protects span j as on cycle span, equal to 2 if *p*-cycle *p* protects span *j* as straddling span and 0 otherwise.

sp_j Spare capacity required on span j .

n^p Number of unit-capacity copies of *p*-cycle *p* in the solution.

d^t The values of demand for each demand pair t (integer).

$f^{t,e}$ Demand units for t^{th} demand assigned to the e^{th} eligible route (integer).

$\lambda_j^{t,e}$ Equal to 1 if the e^{th} working route for the t^{th} demand passes through span j , 0 otherwise.

T_j Total (spare + working) capacity of span j

$AE(p)$ Actual efficiency of the *p*-cycle.

$APE(p)$ A priori efficiency of a *p*-cycle.

n_i^p	Number of copies of *p*-cycle p used to protect span i.
$n_i^{p,L}$	Number of copies of *p*-cycle p required for protection of span i, when the L side of the cycle is used.
$n_i^{p,R}$	Number of copies of *p*-cycle p required for protection of span i, when the R side of the *p*-cycle is used.
$C_{i,j}$	The input matrix element $C_{i,j}$ for the Hungarian algorithm.
CS	Set of low availability spans indexed by *k*.
S-CS	Set of spans, excluding the low availability spans, indexed by j.
ω_k	Working capacity on low availability span *k*.
$\Pi_j^{p_{spk}}$	Equal to 1 if *p*-cycle p_{spk} crosses span j, otherwise 0.
$\chi_k^{p_{spk}}$	Equal to 1 when *p*-cycle p_{spk} protects low availability span *k* as straddling span and 0 otherwise (it will not provide protection to any other span).
$n^{p_{spk}}$	Number of unit-capacity copies of *p*-cycle p_{spk} in the solution.
η	Capacity redundancy = (spare capacity * 100) / protected working capacity.
X_n	Represents the successful operation of link *n*.
$P(X_n)$	Represents the probability of successful operation of link *n*.
$\overline{X}_n$	Represent unsuccessful operation i.e. failure of link *n*.
$P(\overline{X_n})$	Represents the probability of failure of link *n*.
N_w	Total number of working paths in the network. With unit traffic matrix for *n* node network, this will be equal to $n(n-1)$.

N_1	Total number of paths carrying critical traffic which need to be provided dedicated *p*-cycle protection for guaranteed dual failure protection. Neither source, nor destination nodes are of degree 2 or less for these paths.
N_2	The number of paths which are protected against single failure in the network using conventional *p*-cycles. .
T_1	The spare capacity required for protecting N_1 critical paths of the network with dedicated *p*-cycles.
T_2	The spare capacity required for protecting normal traffic (N_2 paths) of the network with SCO model.
ΔT	The percentage of additional capacity required for providing dual failure protection per path

List of Abbreviations

ANSI	American National Standards Institute
APS	Automatic Protection Switching
APWCE	Adaptive Protected Working Capacity Envelope
ARPANET	Advanced Research Projects Agency Network
ATM	Asynchronous Transfer Mode
BGP	Border Gateway Protocol
BLSR	Bi-directional Line Switched Rings
CCITT	International Telegraph & Telephone Consultative Committee
CIDA	Capacitated Iterative Design Algorithm
CR-LDP	Constraint-based Label Distribution Protocol
DCPC	Distributed Cycle Pre-Configuration
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ELT	Expected Loss of Traffic
FIPP	Failure Independent Path Protection
FSC	Fiber Switch Capable
GMPLS	Generalized Multi Protocol Label Switching
H-L	Hop Count Limited
IEEE	Institute of Electrical & Electronics Engineers
IETF	Internet Engineering Task Force
ISP	Internet Service Provider
ITU	International Telecommunication Union
JCO	Joint Capacity Optimization
L2SC	Layer 2 Switch Capable
LAN	Local Area Network
LAS	Low Availability Span
LDPP	Link Disjoint Path Protection

LED	Light Emitting Diode
LMP	Link Management Protocol
LSC	Lambda Switch Capable
LSP	Label Switched Path
MDCPC	Modified Distributed Cycle Pre-Configuration
MFS	Multi-failure Survivability
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NACK	Negative Acknowledgement Message
NCMA	Node Encircling *p*-Cycle Mining Algorithm
NEPC	Node Encircling *p*-Cycle
NSFNET	National Science Foundation Network
OADM	Optical Add-Drop Multiplexers
O-E-O	Optical-Electronic-Optical
OIF	Optical Internetworking Forum
OPA	Optimum *p*-Cycle Allocation
OSPR	Open Shortest Path First
OXC	Optical Cross-Connects
PSC	Packet Switch Capable
PSTN	Public Switched Telephone Network
PWCE	Protected Working Capacity Envelope
RLB	Removal of Loop Back
RLBOPA	Removal of Loop Back with Optimum *p*-Cycle Allocation
RSC	Refine Selected Cycles
RSVP-TE	Resource Reservation Protocol Traffic Engineering
SBPP	Shared Backup Path Protection
SBSP	Shared backup Span Protection
SCO	Spare Capacity Optimization
SDH	Synchronous Digital Hierarchy
SEA-ME-WE-3	South East Asia Middle East Western Europe
SHN	Self Healing Network

SIS	Swarm Intelligence System
SLA	Straddling Link Algorithm
SLSP	Short Leap Shared Protection
SONET	Synchronous Optical Network
SRLG	Shared Risk Link Group
TCP/IP	Transmission Control Protocol/ Internet Protocol
TDM	Time Division Multiplexing
UPSR	Unidirectional Path Switched Rings
VWP	Virtual Wavelength Path
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WP	Wavelength Path
WRLB	Without Removal of Loop Backs
WRLBOPA	Without Removal of Loop Back with Optimum *p*-Cycle Allocation

CHAPTER 1
INTRODUCTION

Human beings are the rare species in the World as they have the ability to think and the ability to express. These abilities created the need to share their thoughts and their feelings. The thoughts and the feelings can be shared in various ways like by speech, body moves, gestures, and facial expressions etc.. The process of sharing is well known as ‘communication’. The speech is one of the most powerful medium of communication; however, human voice can reach only up to a limited distance to convey one’s thoughts. Whereas, the need to share, knows no bars; it cannot be bounded by geographical distances. In ancient times for long distance information sharing, smoke signals, fire signals, drums, semaphore or physical delivery (runners, horses, stage coaches, and carrier pigeons) were used. The same process of sending the signals over a distance for the purpose of communication is called ‘telecommunication’ in modern times.

The invention of telegraph in 1837, later its patent by Samuel F.B. Morse [1] and deployment of first telegraph link between Baltimore and Washington in 1844 can be taken as the starting of the modern telecommunication. This was the first big breakthrough in the field of telecommunication, as the information in the form of electrical signals, was transmitted at a very fast speed almost equal to the speed of light through wired line.

The next logical invention was in 1876 of the telephone by Alexander Graham Bell [2]-[3]. The telephone transmitted the voice signals over wire. Since then, the telephone system has been evolving and now it has become the network of the world's public circuit-switched telephone networks popularly known as PSTN (Public Switched Telephone Network). Traditional PSTN systems were circuit switched, optimized to carry the voice traffic with the transport technology totally based on copper cables. With the advances in optical fiber technology revolution came in the transport technology. Optical fibers offer much higher bandwidths than copper cables and are less susceptible to various kinds of electromagnetic interference and other undesirable effects. This led to the replacement of copper cables in the core networks by optical fibers. To understand how it happened, the brief history of light communication and optical fibers is discussed in the following sections.

1.1 USE OF LIGHT FOR COMMUNICATION

Use of light for communication is not new to the human beings. Light had been used for communication long before the first low-loss optical fiber was invented. In ancient times fires were lit on hills to send the signals for telecommunications. Ancient Egyptians reflected the sun's light to send solar signals. Before the invention of electricity, revolving lenses were used to magnify the small flames in lighthouses. To communicate between ships, lamps were used to send signals using Morse code. In 1793, Claude Chappe developed the first optical telegraph line between Paris and Lille, for a distance of about 230 km [4]. The guided transmission of light was first demonstrated by John Tyndall in 1870; however, it was through water. In 1880 unguided light was used for the transmission of voice up to a distance of 200 m by photophone developed by Alexander Graham Bell.

1.1.1 EVOLUTION OF OPTICAL FIBERS

The development of fiber optic technology provided the required medium for guided transmission of light. The all-glass fiber was first used by Brian O'Brien at the American

Optical Company in his fiberscope, the image-transmitting device, during 1950s. However, this fiber was without cladding. Therefore, excessive optical loss was associated with it. After that, optical fibers with cladding were developed. During the same time period, extensive research was going on in the field of lasers and LEDs (light emitting diodes). In 1957, the idea of using lasers in fiber optics as source for transmission of signals was given by Gordon Gould at Columbia University and after some time by Charles Townes and Arthur Schawlow at Bell Laboratories. The invention of semiconductor lasers in 1962 opened the way for optical fiber communication. These lasers were the most suitable ones for use in optical fiber communication.

At the time when fiber losses were more than 1000 dB/km, two scientists Dr Charles Kuen Kao and Dr. George Hockham were working at the Standard Telecommunication Laboratory in England. In 1966, they suggested in their landmark paper [5] that if the attenuation in optical fibers could be less than 20 dB/km, optical fiber might be a suitable transmission medium for light. They also suggested that the high losses of more than 1000 dB/km were the result of impurities in the glass, not of the glass itself. By reducing these impurities low-loss fibers suited for communications would be produced. Within a few years of the Kao and Hockham's paper, Dr. Robert Maurer et al. developed the fiber with losses less than 20 dB/km in 1970 [6]. They manufactured a fiber with 17 dB/km loss, by doping silica glass with titanium. Very soon in 1977 fibers were developed with theoretical minimum loss for silica-based fibers of 0.2 dB/km at 1550 nm.

1.1.2 OPTICAL FIBERS IN CORE NETWORKS

In 1977 itself, AT&T installed fiber optic telephone systems in Chicago [7] and GTE in Los Angeles [8]. The transmission ranges were 45-140 Mb/s with repeater spacing of around 10 km. In 1979, India also started first optic fiber system at Pune [9].

Initial links operated at 850 nm in first transmission window of silica fiber with a loss of 3 dB/km. These links were designed with GaAs-based sources, silicon photodetectors and multimode fibers. Second window of optical fiber at 1310 nm was more attractive, as losses are around 0.5 dB/km and dispersion was very low. With the availability of sources and detectors in this range operating wavelength shifted from 850 to 1310 nm. This had increased the distance between repeaters substantially, and made the link more suitable for long haul telephone trunks. After 1984, for long haul, single mode fibers are most commonly in use due to their significantly larger bandwidths. These links operate at bit rates of 155 and 622 Mb/s, and in some cases, up to 2.5 Gb/s with repeater spacing of about 40 km. Third window at 1550 nm offers minimum losses of 0.2 dB/km, and hence became suitable for lager data rates and long-span terrestrial and undersea transmission links [10]. The invention of EDFA (erbium-doped fiber amplifier), by David Payne of the University of Southampton, and Emmanuel Desurvire at Bell Laboratories in 1986, reduced the cost of long-distance fiber systems by eliminating the need for optical-electrical-optical repeaters.

The first transatlantic telephone cable to use optical fiber was TAT-8 which was started in 1988. It supported data rates at around 2.5 Gb/s over 90 km repeater spacing. By 1996 the data rate through fibers increased to 10 Gb/s with further advances in lasers and optical receivers. However, the enormous bandwidth of fibers could not be utilized with the speed of available electronic components. To increase the bandwidth utilization, WDM (wavelength division multiplexing) technique proved to be very useful in early 1990s, and very soon commercial WDM systems were deployed all over the world. One such undersea system SEA-ME-WE-3 (Southeast Asia-Middle East-Western Europe) is deployed [10] with two pairs of undersea fibers each having eight wavelengths with a capacity of 2.5 Gb/s per wavelength. With DWDM (dense wavelength division multiplexing) technology the data rate through fibers has touched the figures of around 10 Tb/s within the immense bandwidth of 50 THz or better in the optical fiber technology.

The main benefits of fiber are its exceptionally low loss, allowing long distances between amplifiers or repeaters; and its inherently high data-carrying capacity. Optical fibers offer much higher bandwidths than copper cables and are less susceptible to various kinds of electromagnetic interference and other undesirable effects. All this led to the almost complete replacement of coaxial copper cables by optical fibers in the long haul transmission of PSTN systems.

1.2 First Generation of Optical Networks

Initially regional telephone companies used proprietary architectures, equipment, multiplexing formats, and maintenance procedures for transmission on fiber optic cables. The result was difficulties in networking with each other. The same problem was faced by different countries as they had little in common, and expensive converters were required for transatlantic traffic. Thus the need for standardization became obvious and was fulfilled with the development of SONET (Synchronous Optical Network) by ANSI (American National Standards Institute). A set of parallel CCITT (International Telegraph & Telephone Consultative Committee) recommendations resulted in SDH (Synchronous

Digital Hierarchy). SONET/SDH provided details for grouping, multiplexing, and transmission of information over an optical network. They were devised to ensure the compatibility of optical equipment and services provided by different companies. After the development of these standards, all the long distance telephone voice traffic is carried on optical fiber links using SONET/SDH in the physical layer. Still in the present systems the incredible bandwidth offered by the optical fibers has only been used as a very high-speed channel, replacing copper cables. Optical fibers are acting just as point-to-point links.

1.2.1 DATA TRAFFIC

While PSTN system was evolving to support more and more number of telephone connections, the computer industry was experiencing spectacular progress. From the early mainframe (large room size) computers to desktop computers, had become reality within a short period of time. Organizations, companies, and industries now started having large number of computers, whereas in sixties, they might have had just one or two large size computers. Initially, these computers might have been working in isolation, but at some point of time, data transfer between them became necessity. To fulfill this necessity, the computers of a company or organization were physically connected and resulted in LANs (Local Area Networks). Usually these are privately owned networks. The owner generally provides the physical connectivity in LANs and the topologies used are either bus or ring [11].

To provide communication between computers, hardware as well as software is required. The most widely used software architecture is TCP/IP (Transmission Control Protocol/Internet Protocol).

- ***TCP/IP***

The grandparent of all computer networks the ARPANET (Advance Research Projects Agency Network) was mainly developed by academia and connected many universities and government organizations using leased telephone lines. One of the major goals was high reliability, to provide connectivity even as long as only source and destination are working. The goal was achieved with the software architecture TCP/IP based on packet switching. Later on, IP became ubiquitous protocol that provides simplified data transmission. IP networks and the IP packets are simple and efficient to process and they have greatly reduced the networking overheads.

1.2.2 GROWTH OF INTERNET

Many organizations and companies have developed computer networks independently. This resulted in various networks with different hardware and software. Usually these networks are incompatible as happened with voice traffic before SONET. If a person connected to one network and wants to communicate to a person connected to another network, then he has to go through the gateways [11]. Gateways provide necessary connection and translation both for hardware and software between two different networks. A collection of interconnected networks is called an internetwork or just internet. In other words a collection of LANs connected by a WAN is an internet.

ARPANET, successor of Internet is an example of WAN (Wide Area Network). The TCP/IP became official protocol on Jan 1, 1983 [11]. After that many regional networks interconnected with ARPANET made the expansion of ARPANET very fast. The expansion became exponential when NSFNET (the U.S. National Science Foundation Network) had also connected with ARPANET. Sometimes in the late 1980s, this internet has become Internet. The existing networks started connecting to Internet and the growth continued exponentially, and by 1995 there were several millions of users. This size of Internet is doubling every year [11].

Organizations and companies used their private physical layer for LANs, however WANs used the telephone lines from PSTN which is evolving for more than hundreds of years, and has excellent long haul connectivity in the form of fiber cables. The voice traffic is going on in SONET frames on these fiber cables. The data traffic of computer networks of Internet, in the form of IP packets has also started going on in the SONET frames, as SONET has the capability of carrying IP packets.

The wide spread use of Internet and World Wide Web in recent years has led to an exponential growth in the data traffic to be carried on the fiber cables. Data traffic has started dominating voice traffic by 2001 [12]-[14] and now as per the recent report [6], the data traffic has increased more than ten times the voice traffic.

1.2.3 TRANSMISSION OF DATA TRAFFIC

This new traffic has been carried by using IP network in parallel with voice network. The PSTN operators have started a new Internet Service Provider (ISP) business. The same old infrastructure is used for this new service [14]. The data traffic is bursty in nature and IP packets are used to carry it in the form of bursts. However, the Internet based on TCP/IP has no quality of service and the existing PSTN system only supports circuit switching and hence single quality of service. The characteristics of data traffic are entirely different from that of the voice traffic. To provide quality of service and to utilize the transmission system more efficiently for data traffic, ATM (Asynchronous Transfer Mode) has been devised.

- ***ATM (Asynchronous Transfer Mode)***

The International Telecommunications Union-Telecommunication Standardization Sector (ITU-T, or formerly the CCITT), the ATM Forum, and ANSI have devised ATM to provide a range of service qualities at a reasonable cost, specifically for data services [15]. It has been developed to provide scalable, manageable, a high-speed (multimegabit), multiplexing and switching network with end to end quality of service with low overhead. The ATM network can support any type of traffic including voice, data, and video applications [16]. ATM is the technology that can guarantee predefined quality of service for real time applications with certainty.

ATM layer may be used as service integration layer on top of SONET/SDH. ATM provides a powerful set of capabilities in terms of traffic engineering. Further, it is advantageous because of availability of faster ATM switches, and its ability to provide quality of service guarantees such as bandwidths and delays [17]. It is still the only technology that can guarantee predefined quality of service with certainty for real time applications. These parameters are missing in the IP layer. ATM standards also provide interfaces with IP and SONET/SDH so that it acts as lower layer of IP and upper layer of SONET/SDH. Thus the data traffic is carried on multilayer IP/ATM/SONET/WDM architecture.

These networks, which utilize optical fibers to carry traffic between point-to-point links, are called first generation optical networks. These networks are bit rate, protocol and format dependent i.e. opaque at all switching nodes. In these networks, at each node, all the data (data intended for that node and the data, which is being passed through) have to go through O-E-O (optical-electronic-optical) conversion.

1.3 SECOND GENERATION OF OPTICAL NETWORKS

Significant advances in optical component technologies e.g., optical add-drop multiplexers (OADMs), optical cross-connects (OXCs), erbium doped fiber amplifiers (EDFAs) etc., have made possible, the routing of optical signals based on wavelengths [18], [19]. Further EDFAs, dispersion compensating mechanisms, optical phase conjugators [20] etc. have made possible very long distance, large capacity transmission through optical fibers [21]. The networks with these features are known as second-generation optical networks. They provide an optical layer that offers services to higher layer [22]. For example, optical layer may provide lightpath services to IP networks. A lightpath provides end to end connectivity between two nodes in the network as in circuit switched networks. To set up the lightpath a dedicated wavelength is assigned to it, on each link in its path [22]. In case of circuit switched networks, the entire bandwidth of the lightpath can be given to higher layer and in case of virtual circuit services the bandwidth of the lightpath may be shared between many demands. In the latter case, higher layer combine multiple virtual circuits onto a single wavelength by using time division multiplexing. A major feature of second-generation networks is the transparency of the circuit switched lightpath. A lightpath can be set up with a maximum bandwidth and then the data at any bit rate, in any format and in any form i.e. analog or digital may be transported in this lightpath with only a single condition that total signal bandwidth should not exceed the maximum allowed in the lightpath.

In the multi-layer approach for using optical networks, the layered structure of IP/ATM/SONET/WDM is natural extension. But there is significant functional overlap between various layers. This was justified approach with first generation of optical networks where at each node data has to undergo optical-electronic-optical (O-E-O) conversions. However, this multi-layer approach has some significant disadvantages also. It reduces efficiency and poses increased management cost due to functional overlap and O-E-O conversions at each intermediate node.

The growth of internet is exponential; in fact, internet users are doubling every year. Internet is based on TCP/IP. The ubiquitous IP layer is most commonly used in almost all forms of end user applications. Now it has become clear that common traffic convergence layer is going to be IP [23]-[29]. At the same time, WDM has emerged as the only practical solution to exploit the huge bandwidth of fibers. Therefore, if IP layer can be transported using WDM, significant cost reduction and efficiency enhancement can be achieved. In fact this trend is already evident today with the emergence of IP routers with tunable WDM laser interfaces [18]. The gigabit and terabit IP routers are combined with WDM transmission system for an optimized transport network [23]. To support the IP-over WDM architecture, where the control and data planes are separated, various management and control issues need to be addressed.

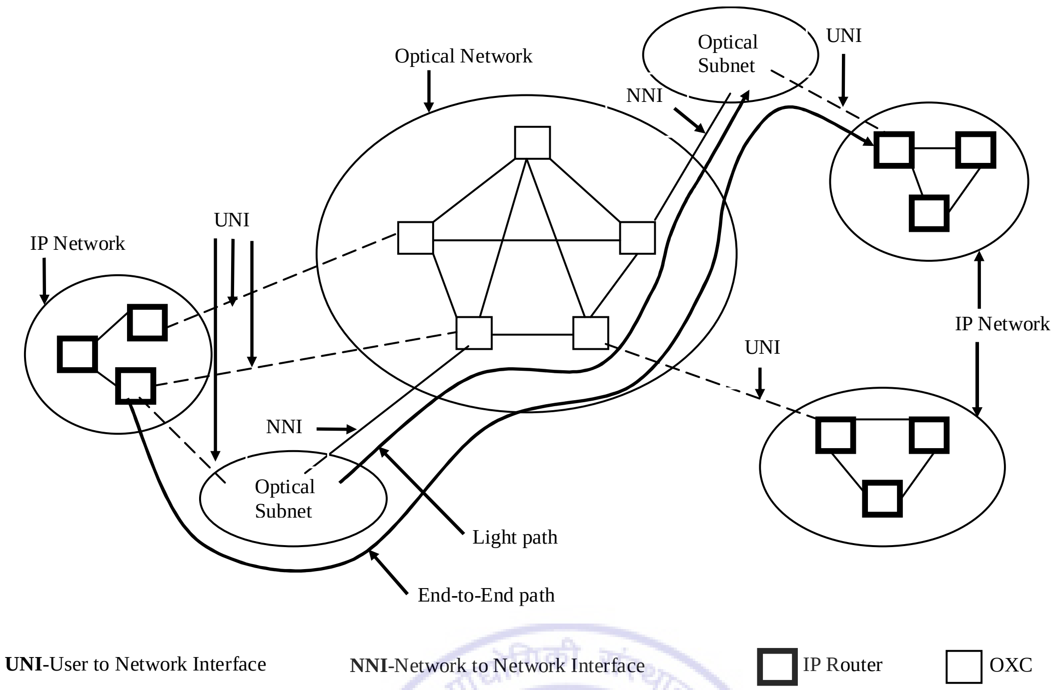

Figure 1-1 An IP over Optical Network

1.3.1 GMPLS CONTROL PLANE

Future optical networks are emerging as optical networks providing services to the IP layer (Figure 1-1). A consensus is emerging in Optical Internetworking Forum (OIF), and also in Internet Engineering Task Force (IETF) and its working groups for using GMPLS (Generalized Multi-Protocol Label Switching) in the control plane of optical layer. It is evident that GMPLS provides the necessary bridge between IP and optical layer [23], [25], [27], [30], [31]. The optical layer provides lightpaths between IP networks. Lightpath is a wavelength channel from source to destination without any O-E-O conversion. Each fiber can have many lightpaths passing through it on different wavelengths using WDM. A pair of nodes may be connected by many fibers. The GMPLS defines five types of interfaces to support multiple types of switching [31], [32]. These are listed below.

- ***PACKET SWITCH CAPABLE (PSC) INTERFACE***

These types of interfaces recognize the packet boundaries and can forward data on the basis of content of packet header which is a 20 bit number.

- ***LAYER-2 SWITCH CAPABLE (L2SC) INTERFACE***

For this interface the label for forwarding information is frame/cell header e.g. Ethernet bridges that use MAC header for forwarding of data.

- ***TIME-DIVISION MULTIPLEX CAPABLE (TDM) INTERFACE***

In this interface forwarding of data is done on the basis of data's time slot. The label could be the serial number of the time slot.

- ***LAMBDA SWITCH CAPABLE (LSC) INTERFACE***

In this case the label is the wavelength on which the data is received. Optical cross connect (OXC) that could operate on the level of an individual wavelength is an example of such an interface.

- ***FIBER SWITCH CAPABLE (FSC) INTERFACE***

This interface uses the information of the local port ID of the fiber. These types of OXC can operate at the level of a single or multiple fibers.

A connection can be established only between or through interfaces of the same type. The connection or established circuit is referred to as Label Switched Path (LSP). To establish, manage and remove the LSPs, communication between nodes is required. The control channels provide the necessary communication for routing, signaling and link management. Link Management Protocol (LMP) [33] defines the procedures for control channel and link management. The LSPs are managed using extensions of Resource Reservation Protocol-Traffic Engineering (RSVP-TE) [34] and Constrain-based Label Distribution Protocol (CR-LDP) [35].

1.3.2 SURVIVABILITY ISSUES

Since fiber has large bandwidth, a large number of lightpaths in a single fiber can exist. Up to 160 lightpaths, each with capacity of 10 Gbps, has been reported in literature [14], [36]. Henceforth, incredibly large traffic volumes can be supported by a single fiber. In this scenario a single fiber failure (single fiber cut) can lead to simultaneous failure of all the lightpaths in the fiber. This will result in failure of thousands of higher layer paths and loss of significant amount of traffic and hence, the revenue. Therefore network survivability issue is very critical in optical networks. In the traditional multi-layer IP/ATM/SONET/WDM approach, the survivability is provided by Automatic Protection Switching (APS) in SONET layer, which is quite robust. It has the capacity of providing recovery within 50 ms in the event of any failure [18]. Therefore, for the success of IP over WDM, survivability and fast recovery in second generation of optical networks should be at least as good as, what SONET provides. Further, the rate of fiber failure is one fiber cut in four days for a network with 30,000 route-miles of fiber [37]. The challenge to provide efficient and fast protection and restoration has to be accepted. Researchers have been working on various schemes to provide efficient and fast protection and restoration in second generation optical networks.

1.4 MOTIVATION AND OBJECTIVES

A lot of protection and restoration schemes have been proposed in the literature for survivability of optical networks. A review of these schemes has been given in Chapter 3. Out of all the available schemes, the *p*-cycles (pre-configured cycles) invented by Grover et al., outperform the other schemes in terms of speed of restoration and capacity efficiency. Therefore, we started working on *p*-cycles. In depth study of *p*-cycles has been carried out, and we have found that still many issues need to be addressed to make best use of *p*-cycles.

The *p*-cycles can be deployed in any real network using distributed cycle pre-configuration (DCPC) protocol developed by Grover's group [37]. The DCPC protocol finds, in the spare capacity of the network, one *p*-cycle in one iteration. If there are many copies of the same *p*-cycle then DCPC has to run many times to find all the copies. Further, in optical networks, all the copies of the same *p*-cycle can be aggregated together and deployed with coarser granularity at the waveband level.

While studying the optimum solutions of *p*-cycle based protection, we found that most of the *p*-cycles used for protection are large and many of them are Hamiltonian (covering all the nodes of the network) cycles. In fact, this is the reason for the capacity efficiency of the *p*-cycles. The price paid for this efficiency is the long restored path lengths after restoration in the event of failure. In many cases, the restored path lengths are found to be more than the number of nodes in the network. Obviously, the reason is the loop backs at the nodes which are repeated in the restored paths. Further, we predict that the restored path lengths will also depend on the allocation of *p*-cycles to the working paths. The reliability of the restored paths with *p*-cycle based protection is also an important performance parameter. Investigations regarding these, will be reported in this thesis.

The *p*-cycles can provide various types of protections like shared span protection, path protection, path segment protection, dual and multiple failure protections, node protection etc.. However, no specialized protection schemes are available for handling low availability spans of the network. The protection of critical traffic also needs some specialized protection techniques.

The work in the present thesis will try to resolve the above issues without compromising any of the features of *p*-cycles. The main objectives are as follows.

- To modify the distributed protocol such that all copies of the same *p*-cycle can be found in one iteration to reduce the computational complexities and to incorporate the advantages of waveband switching in the optical networks designed with *p*-cycle based protection.
- To reduce the restored path lengths by removal of loop backs from the restored paths during second phase reconfiguration without compromising on any of the features of *p*-cycles.
- To develop a distributed protocol for removal of loop backs, so that it can be implemented in a network designed with *p*-cycle based protection.
- To formulate and solve the problem of optimum allocation of *p*-cycles.
- To derive a relationship between the restored path lengths and network parameters.
- To develop a model and study the effect of removal of loop backs on the reliability of *p*-cycles.
- To develop specialized protection techniques for survivability with low availability spans, and for dual failure protection of critical traffic in the network.

1.5 THESIS ORGANIZATION

The work done in the present thesis has been organized in Chapters 1 through 9. In the next chapter, we have introduced the concepts of graph theory, some mathematical operation and concepts related to reliability, which have been used throughout the thesis for the development and evaluation of proposed schemes.

In Chapter 3, various optical layer protection schemes have been reviewed and discussed. It includes various path and span based protection techniques. Further, higher layer and multi layer restoration strategies have also been discussed. Chapter 4 presents an exhaustive review of the work carried out with *p*-cycle based protection. Various methods to form *p*-cycles have also been presented and discussed. The reasons for capacity efficiency of *p*-cycles, the review of various types of protections which can be provided by *p*-cycles, and the reliability issue have also been presented in this chapter.

Chapter 5 deals with DCPC. The modification in DCPC and its effects on number of *p*-cycles, computational complexities and number of switching fabrics have been investigated. It also includes the test networks and simulation conditions which have been used throughout the thesis work.

In Chapter 6, the concept of loop backs is introduced and the mathematical model for analyzing the algorithm for removal of loop backs has also been developed. Further, a relationship between the number of nodes in the network having average nodal degree of two, and restored path lengths with and without removal of loop backs has been given. Finally, performance of removal of loop back has been evaluated for various test conditions.

Chapter 7 presents the distributed protocol for removal of loop back to be implemented in optical networks designed with *p*-cycles based protection. The problem of allocation of *p*-cycles to the paths through the failed span has been formulated and its solution with Hungarian algorithm has been given. The model for reliability assessment has been developed and given in this chapter along with the effects of removal of loop backs on the reliability of the restored paths. The removal of loop backs without and with optimum *p*-cycle allocation has been compared and improvements with latter have been shown. The removal of loop back releases the redundant capacity which can be used for second failure restoration. The effect of removal of loop back on dual failure restorability has also been evaluated and given in this chapter.

The specialized protection techniques for survivability in the presence of low availability spans have been given in Chapter 8. It also presents the techniques for providing specialized protection to the critical traffic through the network. Finally, conclusions, scope for future work and contributions of the present thesis work have been given in Chapter 9.

CHAPTER 2
GRAPH THEORY AND MATHEMATICAL OPERATIONS

The concepts of graph theory have been extensively used in the work done in this thesis. A brief introduction of graph theory and some mathematical operations used is given in this chapter with a view to familiarize the reader with the terms and concepts used throughout the thesis.

2.1 GRAPH THEORY

The formal definition of a graph may be given as -"a graph G consists of a vertex set V, and an edge set E, and a relation that associate with each edge two vertices (not necessarily distinct) called its end point" [38].

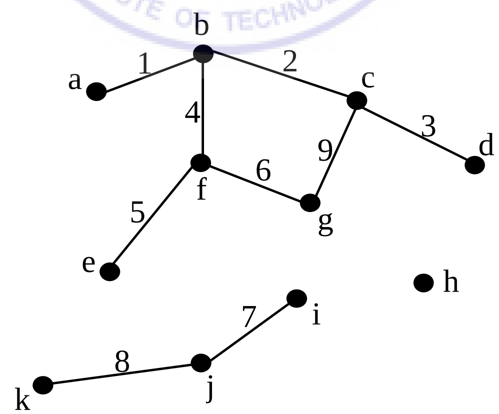

Figure 2-1 A Graph

V (and hence E) are usually taken to be finite sets. A graph can be drawn (Fig. 2.1) on a paper by representing each vertex as a point and each edge as a curve connecting two vertices [39]. Hence, a point in a graph is called a **vertex** and the curve connecting two points is called an **edge.** The two endpoints (vertices) of an edge are **adjacent** and are **neighbors**. If an edge *e* joins v_1 and v_2, then edge *e* can be denoted by $\{v_1, v_2\}$, an unordered pair of endpoints. The edge and its endpoints are called to be **incident** e.g. the vertices v_1 and v_2 are incident on edge *e* and the edge *e* is incident to both v_1 and v_2. The **order** of a graph is the number of vertices in it, i.e. |V| and the **size** of a graph is the number of edges in it, i.e. |E|. The degree of a vertex is defined as the number of edges incident on it and represented as d_v. The average degree of all vertices in a graph is given by $\bar{d} = \frac{2|E|}{|V|}$. In Fig. 2.1, the vertex set V={a, b, c, d, e, f, g, h, i, j, k} and the edge set E={1, 2, 3, 4, 5, 6, 7, 8, 9}, the edges 1, 2, … can be denoted by {a, b}, {b, c}, …, where *a* and *b* are incident on edge *1* and edge *1* is incident to *a* and *b*. The order of the graph is |V| = 11, and its size is |E| = 9.

If the end points of an edge are equal then the edge is called a **loop**. If there are multiple edges between the same pair of vertices then they are called **parallel** edges. A graph with no loop and no parallel edges is a **simple** graph. A graph with parallel edges but no loops is a **multigraph,** and a graph with at least one loop is **a pseudograph**. In a **complete** graph, there is exactly one edge between each pair of vertices. Hence, a complete graph with order N has ${}^{N}C_2 = \frac{N(N-1)}{2}$ edges. In a **regular** graph, every vertex has the same degree.

If the edge *e* can be represented by $e = \{v_1, v_2\}$ an ordered pair with v_1 as origin and v_2 as destination, then the edge will be **directed** edge and graph is known as **directed** graph or **digraph**. If all the directed edges are changed to simple edges, the resulting graph will be known as **underlying** graph of the digraph. Similarly if each edge in a simple graph is replaced by a directed edge, then graph will become **orientation** of the simple graph [39].

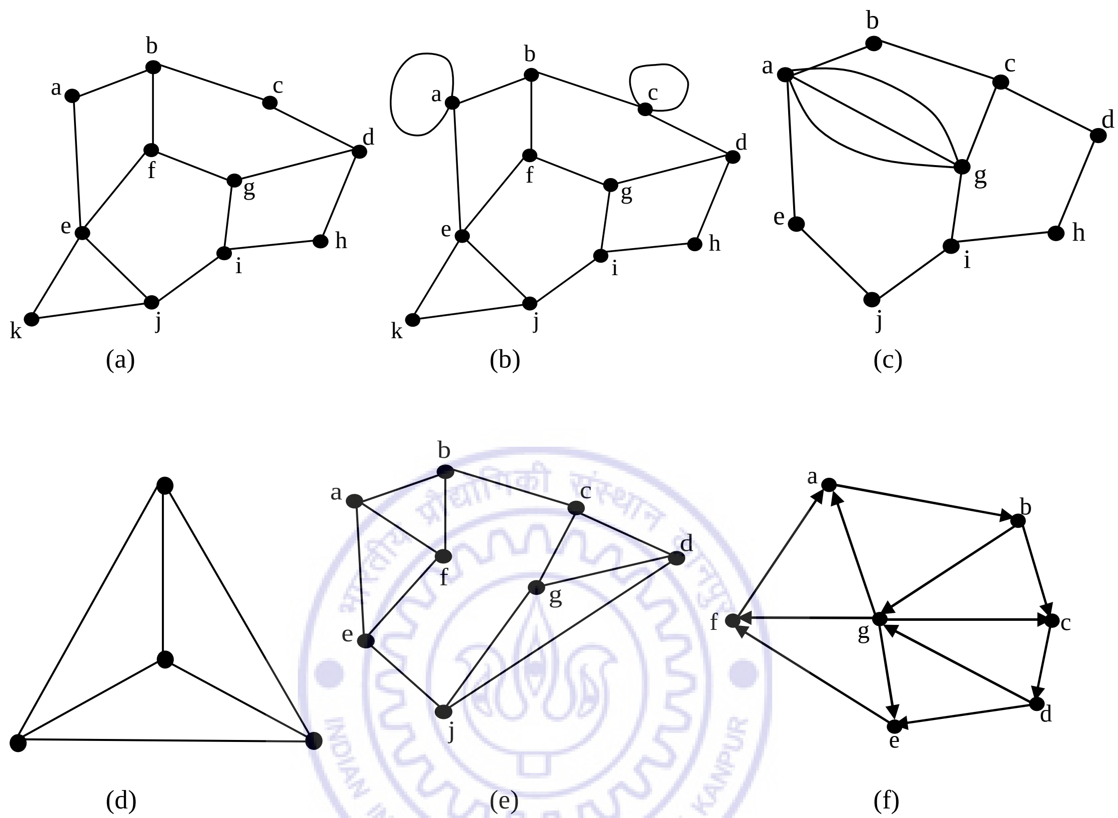

Figure 2-2 (a) A simple graph, (b) a pseudograph, (c) a multigraph, (d) a complete graph, (e) a regular graph, and (f) a directed graph

The two graphs are said to be **isomorphic** if one can be redrawn to look exactly like the other. Thus, two graphs G=(V, E) and $G'=(V', E')$ are said to be isomorphic, if there exists a function $f: V \rightarrow V'$ such that $v_1 v_2 \in G$ if and only if $f(v_1) f(v_2) \in G'$. Then G is isomorphic to G'. The graphs shown in Fig. 2.3 are isomorphic because of the isomorphism defined by

f(a) = 6, *f*(b) = 3, *f*(c) = 4, *f*(d) = 2, *f*(e) = 1, *f*(f) =5, and *f*(g) = 7.

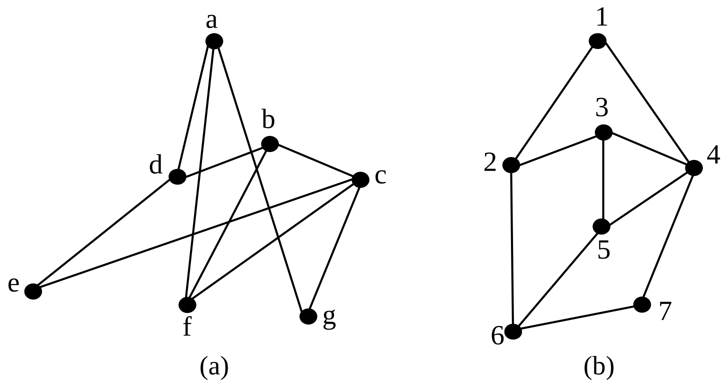

Figure 2-3 Isomorphic graphs

The graph G is said to be **homeomorphism** of the graph G' if a degree two vertex has been removed from G and corresponding edges are replaced by an edge directly incident on the remaining vertices of the edges. The graph shown in Fig. 2.4 (b) is homeomorphic of graph shown in Fig. 2.4 (a).

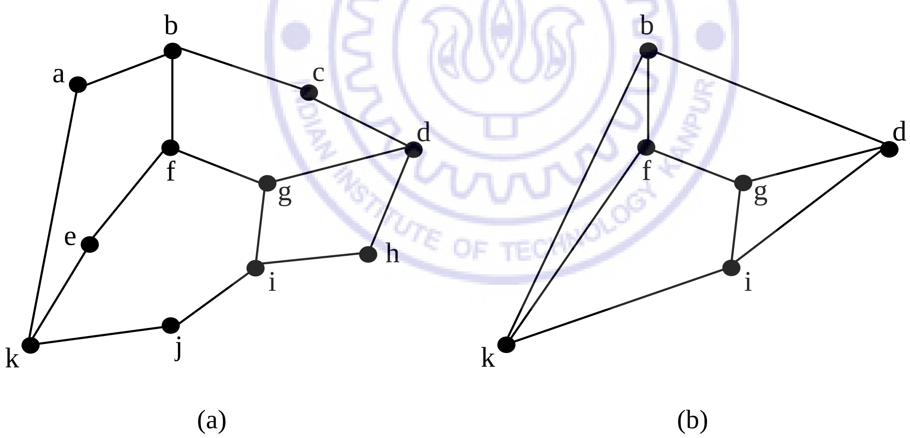

Figure 2-4 Homeomorphic graphs

If a graph can be drawn on a paper in such a way that no two edges intersect each other except at the end vertices, then the graph is known to be **planar**.

A **path** is a graph of the type V=$\{v_1, v_2, v_3, ...v_k\}$ and E=$\{v_1v_2, v_2v_3, ...v_{k-1}v_k\}$. The vertices v_1 and v_k are connected by the path and are known as source and destination respectively. The vertices of a path are ordered i. e. V is an ordered set. The length of a path is equal to the number of edges in it and equal to one less than the number of vertices in it. A **cycle** is a closed path beginning and ending at the same node with equal number of vertices and edges. For a cycle, V $=\{v_1, v_2, v_3, ...v_k, v_1\}$ and E $=\{v_1v_2, v_2v_3, ...v_{k-1}v_k, v_kv_1\}$ with |V|>2. If a cycle contains all the vertices in graph G, exactly once, then it is called a **spanning cycle**. A graph G which contains a spanning cycle is a **Hamiltonian graph**, and the spanning cycle is a **Hamiltonian cycle** of graph G. The cycle which covers all the edges in a graph G is called an **Eulerian cycle** and the graph G is an **Eulerian Graph.**

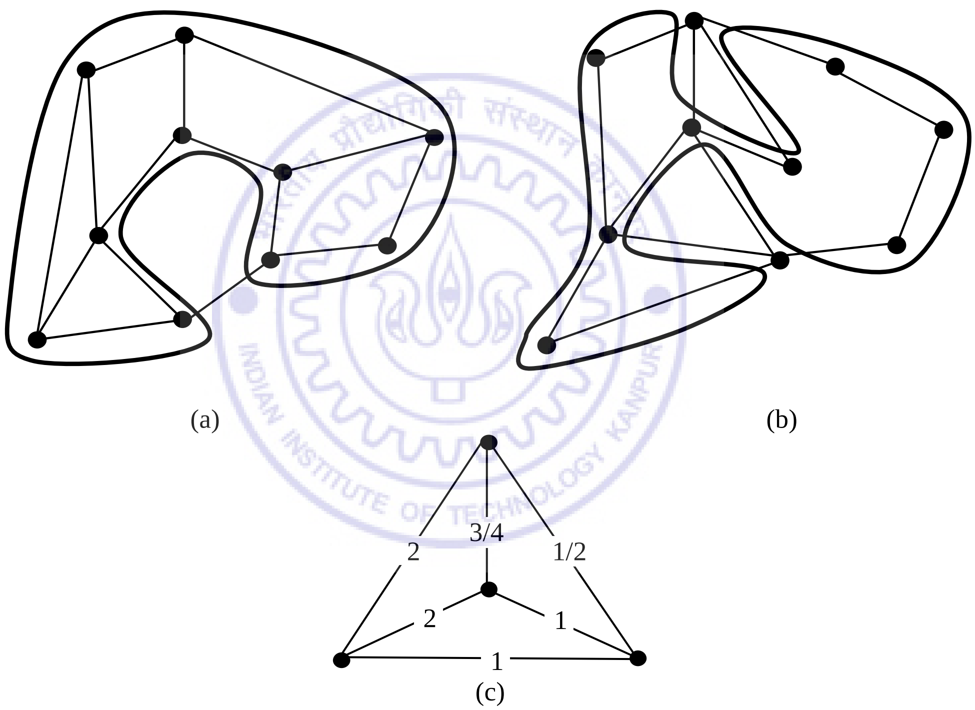

Figure 2-5 (a) Hamiltonian cycle and Hamiltonian graph, (b) Eulerian cycle and Eulerian graph, and (c) weighted graph

If some label (weight) is assigned to every edge of a graph, then graph is called **weighted** graph (Fig 2.5(c)). The weight may represent the length of the edge or the capacity of the edge or some other information related with the edge. The weight of a path is the sum of weights of edges constituting the path.

The communication networks are usually treated as graphs with nodes as vertices and physical connection between nodes as edges. The nodes can be telephone exchanges, digital cross connects, IP routers, ATM switches, optical add drop multiplexers, optical cross connects or other such equipment and edges are the physical connections, mostly optical fibers in present scenario. One unit of transmission capacity is equivalent to a link. The networks are multigraph as there are many parallel links (edges) between two nodes. The term span includes all the links between two nodes. The networks discussed in this thesis are assumed to be undirected graphs as the spans are assumed to have equal capacities for both directions (bi-directional). The weight of a link may represent its capacity, length, cost or some other related value. A path is concatenation of links from the source node to the destination node. The path is established by cross-connecting the links, at the intermediate nodes, with the help of switches.

2.2 MATHEMATICAL OPERATIONS

The ordered sets have been used in the thesis. They are similar to sets except that in ordered sets the order or the sequence of elements matters. The mathematical operations used on the ordered sets are explained below. Let [U] [V] and [W] be the ordered set of nodes. Addition and subtraction operations are defined as follows for the ordered sets.

2.2.1 ADDITION OPERATION

The addition operation (‘+’) [U] = [V] + [W], adds all the elements of [W], except the first one, to the elements of [V] in the ordered form to get [U]. For this operation, the last element of [V] and the first element of [W] should be the same. Hence, if

[V] = [1, 2, 3];

[W] = [3, 4, 5, 6]; then

[U] = [V] + [W] = [1, 2, 3] + [3, 4, 5, 6] = [1, 2, 3, 4, 5, 6].

2.2.2 SUBTRACTION OPERATION

The subtraction operation (‘-’) [V] = [U] - [W], eliminates the elements of [W] from [U] again in the ordered form except the first (last) element of [W] when last (first) elements of [W] and [U] are the same. For this operation [W] has to be the subset of [U], such that either the start nodes or the end nodes are same in both [W] and [U]. This condition is required to maintain the continuity of the paths. Hence, if

[U] = [1, 2, 3, 4, 5, 6];

[W] = [1, 2, 3, 4]; then

[V] = [U] - [W] = [1, 2, 3, 4, 5, 6] - [1, 2, 3, 4] = [4, 5, 6] (first elements of [W] and [U] are the same hence the last element of [W] is retained).

Further if,

[U] = [1, 2, 3, 4, 5, 6];

[W] = [3, 4, 5, 6]; then

[V] = [U] - [W] = [1, 2, 3, 4, 5, 6] - [3, 4, 5, 6] = [1, 2, 3] (last elements of [W] and [U] are the same, hence the first element of [W] is retained).

2.3 RELIABILITY CONCEPTS

The basic reliability concepts which have been used in the thesis are explained below. The reliability of the working path without protection and with protection can be calculated on the basis of these basic concepts [40].

2.3.1 RELIABILITY OF SERIES CONNECTIONS

The reliability of a connection between *A* and *B* which is series concatenation of links (Fig. 2.6) is given as

$$P(S) = P(X_1) \times P(X_2) \times \ldots\ldots\ldots\ldots\ldots\ldots \times P(X_n)$$

$$= \prod_{j=1}^{n} P(X_i) \qquad (2.1)$$

where X_1, X_2, …, X_n represent the successful operation of link 1, 2, …, n respectively and $P(X_1)$, $P(X_2)$, …, $P(X_n)$ represent the respective probabilities of successful operation i.e. reliability of links 1, 2, ..., n respectively. In the above it is assumed that successful operation of a link is independent of other i.e. the failure events in links are independent.

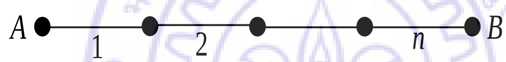

Figure 2-6 Series Connection

Similarly $\overline{X}_1$, $\overline{X}_2$, …, $\overline{X}_n$ represent unsuccessful operation i.e. failure of link 1, 2, …, n respectively, hence $P(\overline{X_1})$, $P(\overline{X_2})$, …, $P(\overline{X_n})$ are probabilities of failure of link 1, 2, …, n respectively and

$$P(\overline{X_1}) = 1 - P(X_1) \text{ or } P(X_1) = 1 - P(\overline{X_1}) \qquad (2.2)$$

2.3.2 RELIABILITY OF PARALLEL CONNECTIONS

The reliability of a parallel connection (Fig. 2.7) having *n* links can be calculated as follows.

For complete failure of connection all *n* elements of the parallel connection have to fail simultaneously. If $P(\overline{S})$ is the probability of failure of the connection, then

$$P(\overline{S}) = P(\overline{X_1}) \times P(\overline{X_2}) \times ....P(\overline{X_n})$$

$= 1 - P(S)$ as success and failure are mutually exclusive events, or

$$P(S) = 1 - P(\overline{S})$$

$$P(S) = 1 - ([1 - P(X_1)].[1 - P(X_2)]..........[1 - P(X_n)])$$

$$= 1 - \prod_{j=1}^{n} [1 - P(X_i)] \qquad (2.3)$$

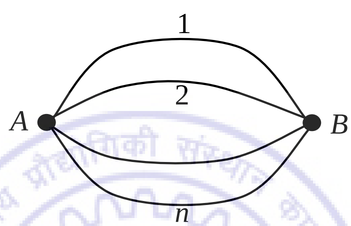

Figure 2-7 Parallel connection

2.3.3 Reliability of Mixed Connections

The mixed connections can be divided into two configurations which are general parallel series configuration and general series parallel configuration. The reliabilities of these configurations are given below.

- ***General Parallel Series Configuration***

The reliability of a connection which is having parallel series configuration is given as

$$P(X) = 1 - \prod_{i=1}^{k} \left[1 - \prod_{j=1}^{n_i} P(X_{ij}) \right] \qquad (2.4)$$

for k branches, each having n_i elements in series (Fig. 2.8).

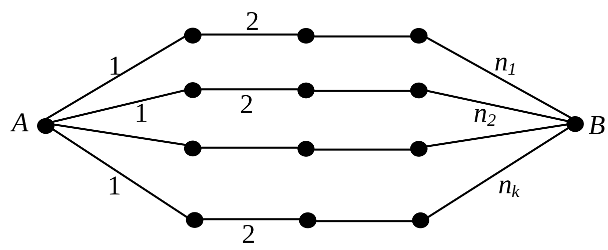

Figure 2-8 Parallel series connection

- ***General Series Parallel Configuration***

The reliability of series parallel connection having k series elements and each having n_i elements in parallel (Fig. 2.9) is given by

$$P(X)=\prod_{i=1}^{k}\left[1-\prod_{j=1}^{n_i}\left(1-P\left(X_{ij}\right)\right)\right]. \quad (2.5)$$

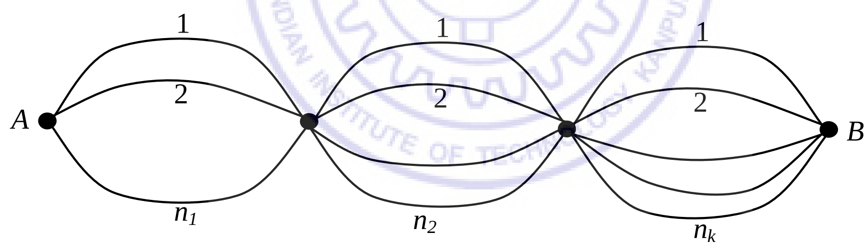

Figure 2-9 Series parallel connection

2.3.4 Reliability of a Path

The reliability of a working path which is concatenation of links is basically a series connection and hence, its reliability can be calculated by using Equation 2.1.

The reliability of a working path (a. b, c, d) which is protected with link disjoint path (a, e, f, g, d) can be calculated with the help of mixed configuration Equation 2.4 using the formula given below

$$P(X) = 1 - \left[1 - \prod_{j=1}^{n_1} P(X_{1j})\right]\left[1 - \prod_{j=1}^{n_2} P(X_{2j})\right], \tag{2.6}$$

where 1 and 2 are the primary and link disjoint secondary paths respectively. The number of elements in primary path, n_1, and secondary path, n_2, are equal to 3 and 4 respectively (Fig. 2.10).

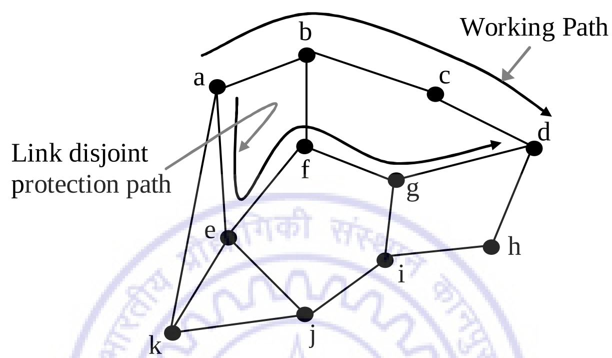

Figure 2-10 Reliability of a protected path

The concepts and definitions given in this chapter have been used throughout the thesis for development and evaluation of various schemes.

CHAPTER 3
SURVIVABILITY SCHEMES[1]

Survivability is an important part of optical networks as huge amount of data is being carried by these networks. Survivability is the ability to provide services during failures. Basically, the failures can be of two types, component failure and fiber cuts. Due to component failures the transmitter or receivers may fail, or it could result in complete node failure. However, the failure rate for transmitters and receivers are 10,867 FIT[2] and 4311 FIT respectively [41]. The failure rate in terms of fiber cut, for long haul networks, is 3 cuts for 1000 miles of fiber annually, about one fiber cut in four days for a network with 30,000 route-miles of fiber [37]. The list of reasons include all the causes like cable dig-ups, human errors in the form of wrong cuts during maintenance, rodents bite, vehicle damage to aerial cables, and of course natural hazards. As per [37], 160 reported fiber optic cable cuts in the 1990s were single-failure events in the United States. The mean times to repair (MTTR) are 2 hours for equipment and 12 hours for cable cut. Therefore, the networks are affected hundreds to thousands times more due to cable cuts as compared to equipment or node failures. Hence, the network survivability issues are mostly dealt with cable cuts i.e. span or link failures. In the following paragraphs, we will provide an overview of the various failure recovery schemes, mainly concerned with survivability during single failures [42], [43].

[1] The work presented in this chapter is based on the previously published work in [42], [43].

[2] 1 FIT=1 failure in 114,155 years

3.1 PROTECTION AND RESTORATION

The network failure recovery schemes can be broadly classified into two categories viz. Protection and Restoration, as shown in Fig.3-1. Protection is defined as pre provisioned failure recovery [14], [18], [30], [44]. The back up path (secondary path or alternate path) which is link disjoint and may be node disjoint also with the primary path, is set up along with the primary path. Usually the same routing protocol is used after eliminating the links used for setting up the primary path, to determine the link disjoint back up path. Similarly if the nodes in the primary path (except source and destination) are also eliminated while computing back up path, the back up path will be link and node disjoint. The primary path is used to transmit the data and back up path is reserved for use in the event of failure. After the detection of failure, the switches are re-configured to use the back up path. These schemes can provide guaranteed protection since the demand set up completes only if the secondary path is also available. Secondly, these schemes can provide fast recovery because the back up path computation is already done and in the event of failure, only the failure detection and switch reconfiguration has to be done. However, resource utilization is not efficient due to reservation of resources for back up paths.

Restoration schemes refer to dynamic recovery after the onset of failure [14], [18], [30], [44]. The restoration involves detection of a failure, new path computations for the failed connections and reconfiguration of switches for the restoration path. These schemes provide efficient utilization of resources. However, successful recovery cannot be guaranteed since enough resources may not be available at the time of failure. Further time required for recovery is more [44]. Usually optical layer can provide fast protection while higher layers can be used for intelligent restoration.

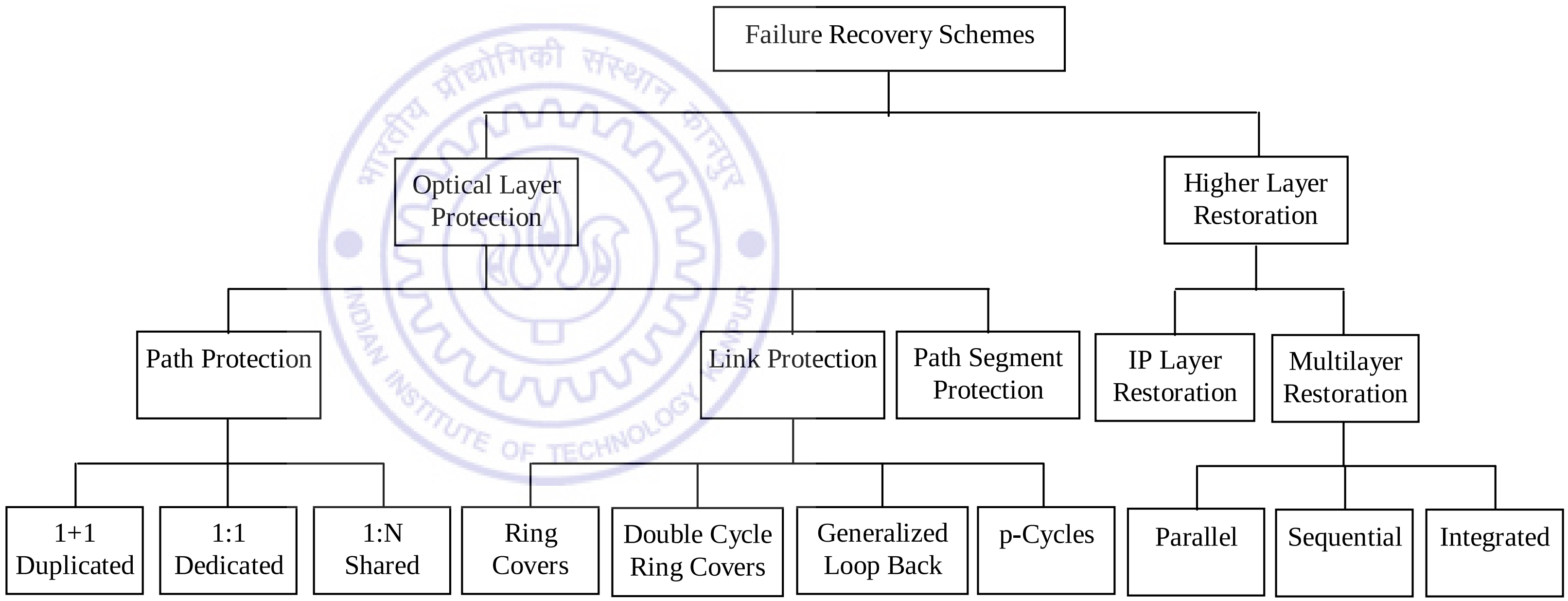

Figure 3-1 Failure recovery schemes

3.2 OPTICAL LAYER PROTECTION

The optical layer protection schemes can be divided into path protection, link protection and generalized path-link protection schemes. These schemes can be implemented in static as well as dynamic environments. In the static case, the traffic demands are fixed and in the dynamic case, the traffic demands are changing and the working paths are established and removed as per the traffic requirements.

3.2.1 PATH PROTECTION

The entire lightpath from source to destination is protected in these schemes. In the event of failure, fault localization is not required, instead traffic is switched over to link and node disjoint backup path. These schemes inherently provide the protection against node failures also as backup paths are link and node disjoint. Further, the schemes are suitable to the optical networks where the intermediate nodes may not have the monitoring capability. Various path protection schemes are shown in Fig.3-2. These optical layer path protection schemes are 1+1 (duplicated), 1:1 (dedicated), and 1:N (shared).

- ***1+1 DUPLICATED PATH PROTECTION***

In 1+1 duplicated path protection (Fig.3-2(a)), the source transmits on both primary and backup paths. In the event of failure, the receiver at destination simply switches to the alternate backup path. This approach is very simple and very fast. However in this approach, the network resource utilization is very poor [45].

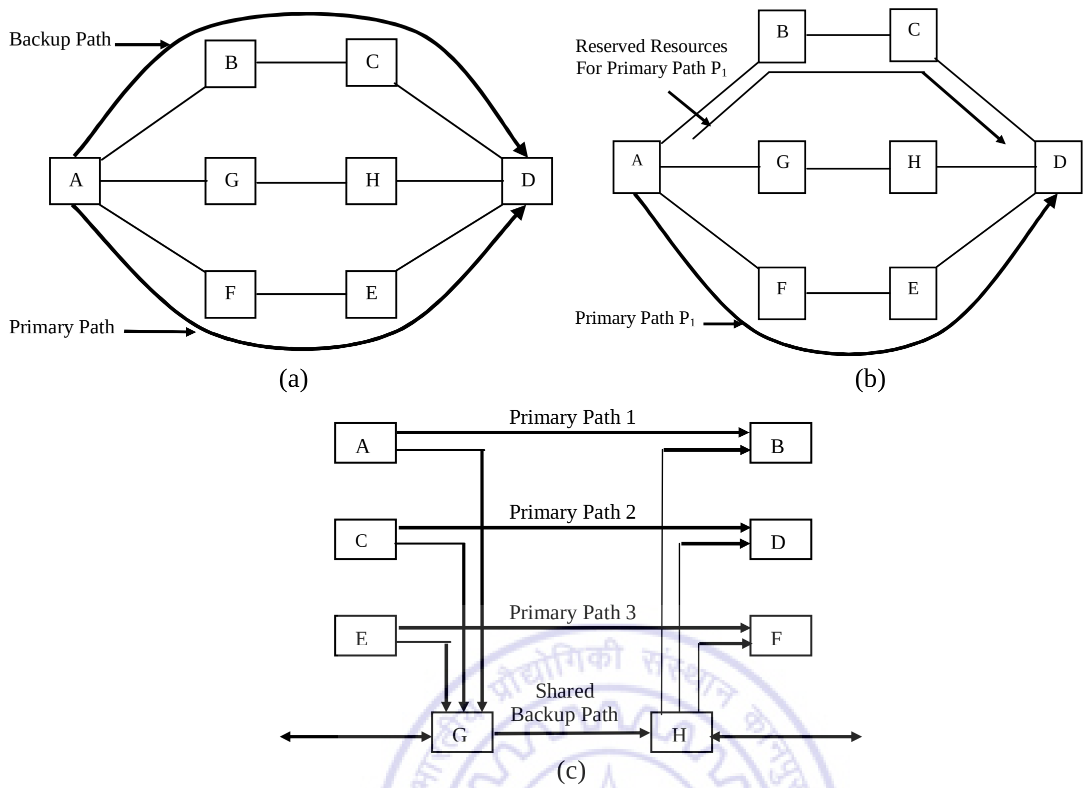

Figure 3-2 Path protection schemes, (a) 1+1 duplicated path protection, (b) 1:1 dedicated path protection, (c) 1:N shared path protection

- ***1:1 DEDICATED PATH PROTECTION***

The 1:1 protection is also known as dedicated path protection (Fig. 3-2(b)). Here the resources for the backup paths are reserved at the time of connection set up. The resources are reserved as backup for respective primary lightpath only. They cannot be shared as back up path for some other primary lightpaths. However, the resources can be used to carry some low priority (pre-emptable) traffic. In the event of failure, the low priority traffic through back up path is dropped and traffic to be protected is directed through backup path.

The 1+1 and 1:1 protection schemes have been compared in [46] for resource utilization. In this study, the primary and backup paths and the resources such as total number of fibers, OXCs etc. have been selected optimally to minimize the total facility cost. The total facility cost includes the cost of fibers and cost of OXCs. It has been found that to minimize the total cost, the ratio of fiber length in the 1+1 & 1:1 schemes is approximately 1.6. Almost the same ratio of 1.6 comes out for OXCs.

A lot of work has been reported in the literature on dedicated path protection schemes and their variants. Many aspects of dedicated path protection have been covered. The scheme and its variants have been tested for bi-directional WDM transmission, resulting in higher system capacity and lower call blocking probability [47]. The scheme has also been used with waveband switching [48]. Requirement of more resources, one of the drawbacks of the scheme, has been overcome in [49] with sharing of resources, and in [50] with dynamically routed Streams algorithm.

- ***1:N SHARED BACKUP PATH PROTECTION***

The 1:N protection is shared backup path protection (SBPP) shown in Fig.3-2(c). At the time of connection setup, backup path resources are also computed and reserved. The reserved resources can also be used to provide protection to some other primary path. However, the primary paths sharing the backup should be link and node disjoint. Hence a single failure cannot affect more than one primary lightpath [30], [51], [52].

To ensure the above condition Shared Risk Link Group (SRLG) concept can also be used [53], [54]. An SRLG is a group of lightpaths having a common element whose failure can lead to failure of all the lightpaths in the group. For example, if a single fiber is cut then all the lightpaths through that fiber will be affected. Hence all the lightpaths using this fiber belongs to one SRLG. Similarly the conduit carrying multiple fibers may define another SRLG. Therefore primary paths not having any common SRLG may share the backup path. The concept has been extended to include nodes also in the shared risk group [55], and a mathematical formulation has been developed to solve the problem of SBPP. In [56], it has been proved that SBPP problem in dynamic scenario is NP-complete, and heuristics have been developed to find the pair of working and backup paths in dynamic environment.

The SBPP is most preferred form of path protection due to its resource efficiency, and a number of methods are available to find the working and its shared backup paths. The comparison of all such methods has been given in [57]. SBPP has also been implemented with span protection technique of *p*-cycles [58]. The SBPP has been provided with failure independent path protecting (FIPP) *p*-cycles with the advantage of pre-connected backup resources, thus, providing fast restoration [59].

One of the important performance issues in this scheme is finding the new backup paths if protection is activated for some failed primary path.

3.2.2 LINK PROTECTION

Another mechanism of protection is called link protection. These schemes are designed basically to provide Automatic Protection Switching (APS) of rings in the optical mesh networks. The protection mechanism for these schemes is fast, distributed and autonomous [60].

Any lightpath can be considered as different links being put together end-to-end. Each of these links can be provided individual protection. In case of a link failure, a backup path replaces only the faulty link, other links in the lightpath remain same. Due to smaller scale of link and localization of fault, link protection schemes are faster in response. However, due to local recovery (Fig.3-3) the total number of hops may be more and resource utilization may be less efficient. Another very important feature of link protection is that it can be preplanned once and for all since it is not dependent upon specific demand patterns [61]. With increased speed, the issue of identification and localization of faults and hence switchover to protection link become important. One needs to look into how this will be implemented efficiently. Some link protection schemes are as follows.

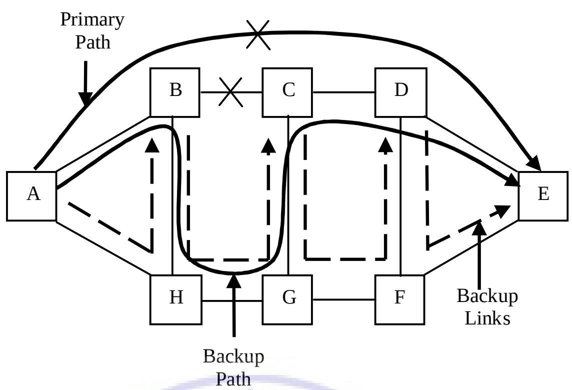

Figure 3-3 Link Protection

- ***RING COVERS***

The mesh network is presented as graph in which node represents a vertex and each link is represented as edge. The entire network is divided into smaller cycles (rings) in such a way that each edge comes under at least one cycle. There is one extra fiber for protection along the cycle. The protection fiber along the cycle protects the whole cycle. In this approach, an edge may be covered by more than one cycle. With fiber based protection every cycle requires four fibers (two fibers for bi-directional working paths and two for bi-directional backup paths). Therefore an edge covered by two rings requires eight fibers, and an edge covered by *R* rings requires *4R* fibers. Thus the fundamental problem is to minimize the redundancy of protection fibers. However in most cases, the redundancy required is more than 100% [61], [62].

- ***DOUBLE CYCLE RING COVERS***

The mesh networks are represented as directed graphs (digraphs). Each edge of the digraph has a pair of unidirectional working fiber (bi-directional working link) and a pair of unidirectional back up fiber (bi-directional protection link). Thus each edge is covered by exactly two rings. This method reduces redundancy to exactly 100%. All these digraphs are established at the time of setup of network. For a planar graph having N vertices ($N \geq 3$) and M edges, the total no of faces will be F= 2+M-N. This includes F-1 inner faces and one outer face. Thus the required set of protection cycles can be obtained as in [60] by identifying all the faces of planar graph. All the inner faces are covered in a certain direction (say anti-clockwise). The outer face is covered in the opposite direction (i.e., clockwise) as shown in Fig. 3-4.

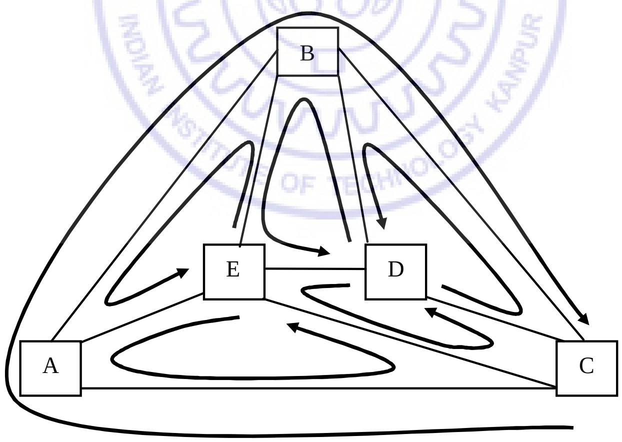

Figure 3-4 Double cycle ring covers

In non-planar graphs, heuristics are used to find the double cycle ring covers. These cycles can then be used as rings to recover traffic. In Fig. 3-5, two possible double cycle ring covers are shown [61] for another fiber topology. In all these cases, four fibers are used and the recovery is fiber-based recovery i.e. all the traffic on one fiber is transferred to another as such in the event of failure. Protection granularity is at the level of fiber. With double cycle ring covers, to recover a failure on link AB (Fig. 3-5), the traffic which is going from A to B may be recovered by Ring 4 through ADCEFGHB, and the traffic in the reverse direction i.e. from B to A is recovered through Ring 1 i.e. BCDA. The two directions on a link will, therefore, have different delays in their restoration times and may cause different timing jitters.

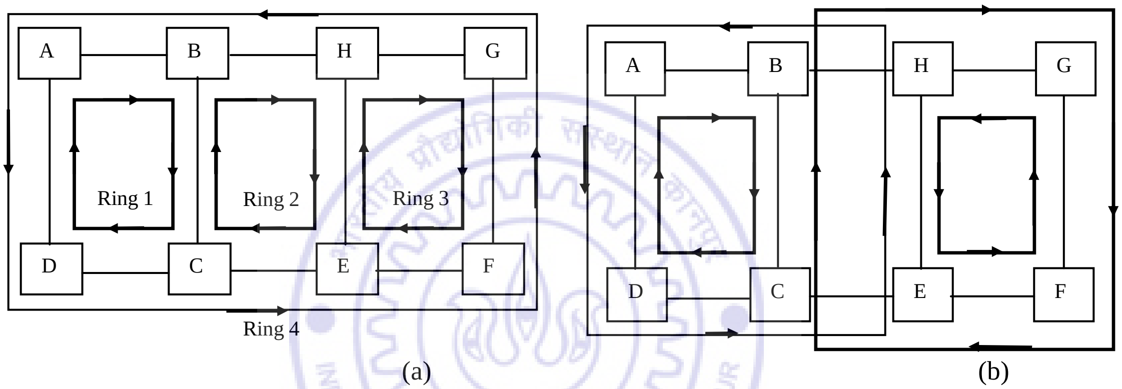

Figure 3-5 Double cycle ring covers, (a) Ring 1, Ring 2, Ring 3 are in clockwise direction, Ring 4 is in anti-clockwise direction, and (b) another possible double cycle ring cover

- ***GENERALIZED LOOP BACK RECOVERY***

Application of ring recovery schemes (ring covers and double cycle covers) to mesh based networks requires more hardware, and hence it is more expensive. Further, as nodes are added or networks are interconnected, ring based structures may be difficult to preserve, thus limiting their scalability. Therefore, another approach more suitable to mesh networks has evolved [61], [63] and is known as Generalized loop back recovery. This method is applicable to arbitrary two-link-redundant and two-node-redundant networks to restore services after the failure of a link or a node respectively. A two-link (node) redundant network remains connected after the failure of a link (node). As in ring cover schemes, network is represented by graphs and failure of a link (node) is mapped to the disappearance of an edge (vertex) in the corresponding graph. In generalized loop back, pair of conjugate digraphs are used for routing primary path and reservation of protection path respectively. Traffic flows in the primary digraph and protection is provided through the use of its conjugate, the backup digraph. These digraphs are calculated only once before the network is put on line for the first time. The heuristic algorithms have been proposed [61] to calculate the recovery loops. In the event of failure, nodes adjacent to the failure simply flood the pre-established backup digraph with traffic of the failed link.

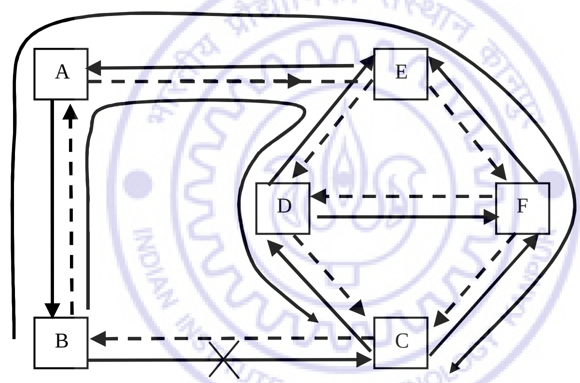

Figure 3-6 Generalized loop back recovery

Consider Fig. 3-6, for simplicity, only unidirectional conjugate digraph is shown. The primary digraph is shown in solid lines and backup digraph is shown in dashed lines. Let's say there is failure in link BC. The traffic is switched over to backup digraph. The backup digraph is flooded with the backup traffic by node B and the backup traffic finds its way to node C. There can be two possible backup paths (B A E D C) and (B A E F C) for the traffic. The protocol ensures that only the traffic, which arrives at a node first, is forwarded to the output ports. Traffic, which arrives subsequently, is simply discarded and the node that sends out this traffic is notified by means of a negative acknowledgement message

(NACK). After receiving a NACK, the node stops forwarding traffic to the corresponding out put port. Therefore only one of the two possible paths is actually established.

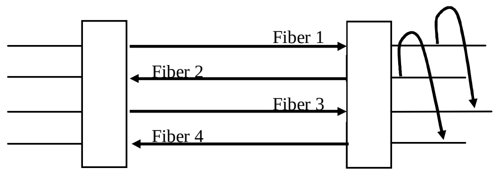

Figure 3-7 Fiber based recovery

In generalized loop back recovery, the protection is fiber based i.e. the entire traffic carried by a fiber is backed by another fiber. For bi-directional traffic flow, fiber based restoration requires four fibers as shown in Fig.3-7. Here fiber 1 and fiber 2 carry primary traffic. Backup is provided by fiber 3 for fiber 1 and by fiber 4 for fiber 2. Loop back recovery scheme is further extended to WDM based loop back recovery, where protection paths are reserved at wavelength level. It requires only two fibers. Fig. 3-8 illustrates WDM based recovery. Primary traffic is carried by fiber 1 on λ1 and by fiber 2 on λ2. Back up is provided by λ1 on fiber 2 (for λ1 on fiber 1) and by λ2 on fiber 1 (for λ2 on fiber 2). The main advantage of WDM based loop back recovery system over fiber based system is that only two fibers are required in the former, whereas at least four fibers are required in the latter.

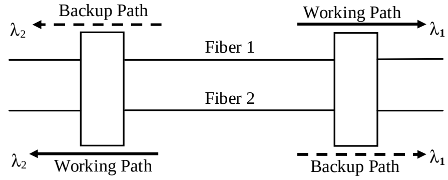

Figure 3-8 WDM based recovery

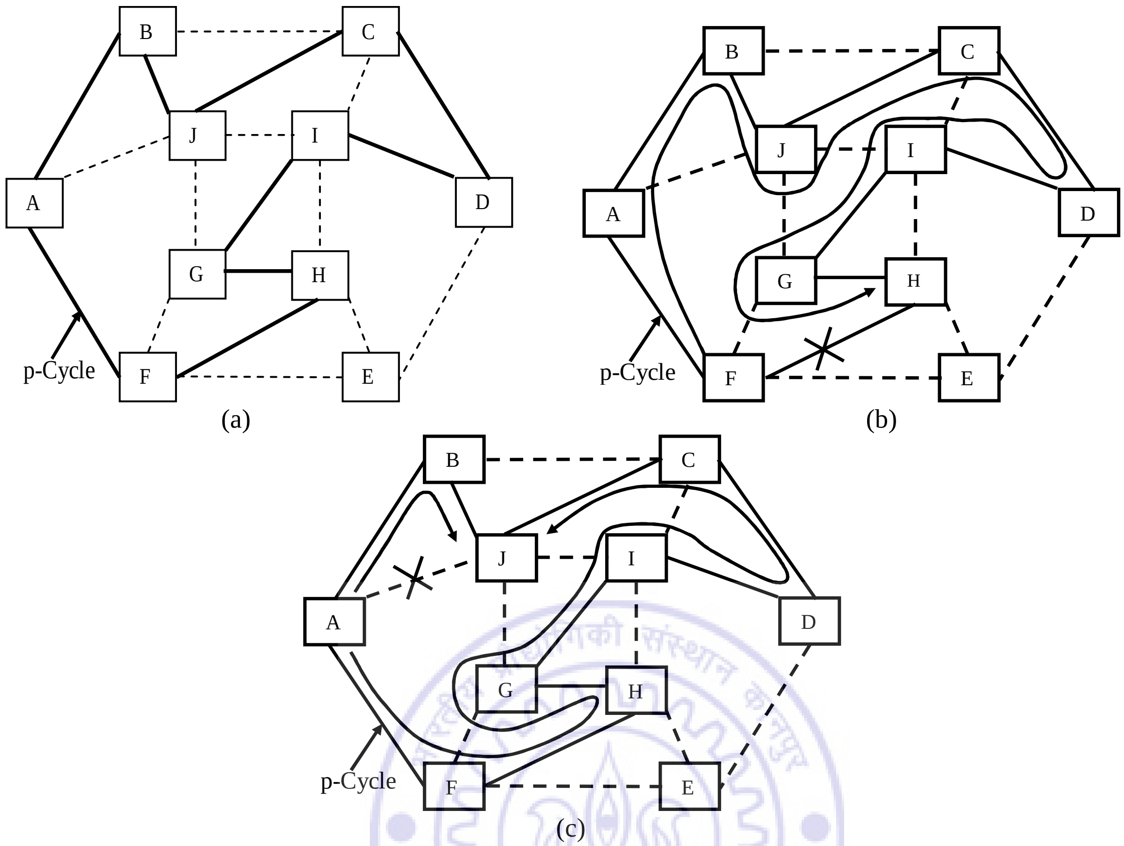

Figure 3-9 ***p*-Cycles, (a) pre-connected spare resources, (b) failure on *p*-cycle, (c) failure on straddling link**

- ***P-CYCLES***

The recovery is very fast (50 ms for SONET rings, discussed in the next chapter) in ring-based networks. However, these networks are inefficient and inflexible [64] as compared to mesh-based networks. *p*-Cycles are the result of efforts to obtain ring like speed and mesh like efficiency and flexibility. The spare capacity of the network is pre-connected to form a closed structure analogous to ring. The closed structure can now provide protection on the shared basis to all the on-cycle links as well as chords (straddling links) of the closed structure. These closed structures are called *p*-cycles. Since spare capacity of the network is pre-connected, hence, only two switching actions (as in rings) are needed at the end nodes of the failed link, to switch the traffic on the back up path, in the event of failure. Fig. 3-9(a) shows an example of *p*-cycle. Solid lines represent the *p*-cycle. This is pre-connected cycle of spare resources in the links. Fig. 3-9(b) shows the failure on the cycle. In this type of failure, the *p*-cycle recovery acts as ring recovery and the traffic of the failed link is switched to the other side of the cycle. Fig. 3-9(c) shows the recovery in case of straddling link failure. A straddling link is one that has its end nodes on the *p*-cycle, but itself is not the part of the *p*-cycle. In case of straddling link failure 'AJ', two protection paths are available viz. 'ABJ' and 'AFHGIDCJ'. The key difference between *p*-cycles and any ring or cycle cover is the protection of straddling link failures. The efficiency of covering these links is double than that of the on-cycle failures because two backup paths are available from each side of the *p*-cycle.

It has been found [64] that a set of *p*-cycles can cover all span failures with three to six times less capacity than required with ring covers. Hence, *p*-cycles offers mesh like capacity efficiencies. Another advantage is due to the fact that *p*-cycles are formed in the spare capacity only. Hence, they can be rearranged as per the changing traffic patterns as needed. They are formed only after routing of the working paths. Hence, *p*-cycles will not affect the flexibility of mesh networks. However, several *p*-cycles may be required to cover an entire network, hence management of *p*-cycles becomes very critical.

The *p*-cycle technique has combined the advantages of the path and the span protection techniques as well as that of ring and mesh protection techniques. The work in this thesis is based on the *p*-cycle technique. Hence, the *p*-cycle technique will be discussed in detail in the next chapter.

3.2.3 PATH SEGMENT PROTECTION

The scheme has been evolved to combine the advantages of path and link protection schemes. In this scheme, instead of a path or a link, a segment of the path is protected. Every segment will have its own backup path, and in the event of failure in a segment, the traffic is switched over to the backup path of the segment. Now, even those paths which may have some common links may share the backup path in a segment in which the paths are link disjoint. Thus, it provides more capacity efficiency than link protection schemes, and as segments are shorter than path, restoration is fast. This scheme has also been called Short Leap Shared Protection (SLSP) [54]. The working of this scheme is shown in Fig. 3-10. The primary path P1 is divided into two segments, segment1 and segment2, then for each segment a separate backup path is provided.

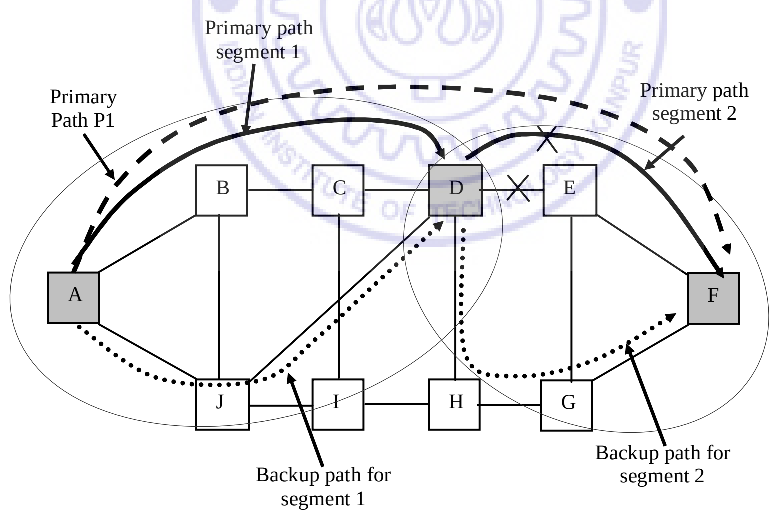

Figure 3-10 Path segment protection

Two variants of the scheme are available in the literature, either the working path is divided into multiple segments or network itself is divided into sub-domains. The shared backup paths are found for each segment of the working path or for the portion of the working path in each sub-domain. Now, the link disjoint constraint of the SBPP is to be applied to a segment or sub-domain only.

How to divide a working path into several segments is an important problem in the field of path segment protection. In [32], [54], [65]-[69] various heuristics and integer linear programming models have been developed to divide the working path into optimum set of segments, mostly to minimize the spare capacity or to increase the restoration speed. The same concept has been used in the dynamic scenario to completely restore the paths in multi-link failures which results in at the most one failure in any SRLG [68]. The main objective of all the models is to provide fast restoration with minimum capacity. All the models and heuristics make tradeoffs between objectives and complexities. The sub-domain division of the network, to increase the restoration speed and to minimize the spare capacity has been discussed in [70]-[72].

The advantages of this scheme are fully distributed computing process, service recovery time guarantee by limiting the size of segments or sub-domains, capacity efficiency, and scalability. However a major disadvantage is the increase in signaling complexity.

Various protection mechanisms, performed in the optical domain have been discussed in the previous sections. These schemes offer several advantages as well as disadvantages. In the following sections, their merits and demerits are presented.

3.2.4 MERITS

- Optical layer is relatively closer to most of the usual faults that occur such as cable cuts. The detection of failure is fast for this layer. The amount of signaling required to perform protection is less. Hence failure recovery in optical domain is expected to be faster, compared to those provided by higher layers.

- Optical layer failure recovery can protect many services, which do not have built-in recovery mechanism or whose recovery mechanism is slow (e.g. IP services).
- The optical layer provides lightpath to higher layers. A single lightpath may be used to carry a large number of higher layer connections and an optical fiber may carry several such lightpaths. Hence even a single failure (e.g. link, node or fiber cut) may affect a very large number of higher layer connections [73]. However, protection in the optical domain may involve just a 2x2 switch to switch over to another fiber in case of fiber cut or by passing the link (node) in case of link (node) failure. Hence, protection can be done with coarser granularity in the optical domain reducing the switching cost significantly.
- The additional resources required for protection in the optical domain are shared among multiple higher layer connections and hence, the resources can be better optimized by optical layer protection schemes.
- Optical layer failure recovery schemes allow building the virtual topologies, which may be resilient to single fiber failures [74]-[76].

3.2.5 DEMERITS

- The optical layer protection schemes can not handle the failure of higher layer electronic equipment or nodes.
- It cannot monitor higher bit error rates hence in this case, protection switching cannot be done in the optical layer [61].
- Due to coarser granularity it is very difficult to provide different levels of protection to different classes of traffic.
- The alternate paths are not optimized and hence may be very large.

In optical layer protection schemes, in the event of a failure, the fault is detected and with the help of simple switching the traffic is switched over to a pre-computed backup path for which resources are already reserved. However, these schemes cannot protect the faults occurring at higher layers e.g. network interface card failures & IP router (node) failures. In many network-operating scenarios, the optical layer protection may not be a technically or economically feasible option. There may be an internet service provider (ISP) operator having a logical network which is based on leased line services from physical layer service providers. Such an operator will require failure recovery schemes which are in his own control i.e. in the logical network plane. This is either because control of (or may be even knowledge of) the physical layer is not available to him or the optical layer service provider may charge more to provide failure recovery in the optical layer.

At a higher layer, an alternate path can be worked out on the basis of an algorithm after the failure. Higher layer can also take ‘priorities’ into consideration. Thus the process can be more intelligent. This is known as restoration. However, if no new path was discovered for a failed working path, the traffic carried by that path would be lost. Therefore, restoration schemes cannot be used for guaranteed survivability. Further, this process is more time consuming than protection. Hence this mechanism is not used alone. Usually this works along with the optical layer protection. In the following sections some higher layer restoration schemes are presented.

3.3 IP LAYER RESTORATION

Conventional IP is connectionless protocol. In IP layer, restorations are best effort in nature. In this layer, to restore the services, the traffic (IP packets) is rerouted by updating routing tables at the nodes. This is done automatically using OSPF (open shortest path first) and BGP (border gateway protocol) with the help of link state and route advertisement messages. However, these are relatively slow processes. For rapid IP restoration an interesting idea is proposed in [77]. Here, the concept of *p*-cycles has been used at the IP layer to protect node (IP router) or logical link failures. If there is failure of any logical link, then the router ports, which terminate the failed link, will be marked as dead, and the usual link state advertisement update process will be triggered. A *p*-cycle has already been assigned to protect the failed link. During the time, in which global routing update is done in conventional IP, the packets to be directed to the dead ports, as per their destination address, are deflected onto the *p*-cycle. The packets are first encapsulated in a "*p*-cycle packet" and then deflected onto the *p*-cycle. This packet contains the address of pre-assigned *p*-cycle and travels through the *p*-cycle. When the packets come at the other end of the failed link via the *p*-cycle, the original IP packet is removed from the encapsulating packet and forwarded on its route towards final destination.

This scheme can be used to restore failure of a single logical IP link between a pair of adjacent routers. For fiber cuts or physical layer failures, which can cause fault multiplication from one fiber cut to several logical link failures in the IP layer, the optical layer protection schemes are best suited.

3.4 MULTI-LAYER RESTORATION

Even the simplified IP over WDM network typically consists of multiple layers. Different protection and restoration mechanism may be present in different network layers. Therefore, two main issues arise with multi-layer survivability,

- All the layers may try to rectify the same fault causing ‘chaos’.
- During faults, spare resources have to be present for being used by each layer.

Multi-layer recovery can combine the merits of optical layer and the higher layer schemes. In order to do this, inter-working between different layers is required. The inter-working between different layers is called ‘escalation’ [14], [18], [78], [79]. Escalation strategies deal with issues such as when to start, stop and how to coordinate activities of protection and restoration mechanisms in different layers. There are three types of escalation strategies

- Parallel strategies
- Sequential strategies
- Integrated strategies

3.4.1 PARALLEL STRATEGIES

In this escalation strategy, different protection and restoration schemes are activated simultaneously in the event of a single failure. When one scheme recovers the failure, all other schemes stop. This is fast and no communication or coordination is required between different protection and restoration schemes. However, they may contend for the same spare resources and may obstruct each other. Therefore efficient spare capacity sharing mechanisms are required. Such resource sharing schemes are given in [79], [80].

3.4.2 SEQUENTIAL STRATEGIES

In these strategies, the protection and restoration schemes in different layers can be activated sequentially in an order. Either they can be activated from top-to-bottom i.e. top-down strategies or from bottom-to-top i.e. bottom-up strategies. In the top-down approach, the recovery actions are activated in the top (highest possible) layer, and the lower layer schemes are activated only if higher layer cannot restore the traffic. An advantage is that it can differentiate traffic with respect to the service types. Thus high priority traffic may be restored first. However, this is more time consuming approach. In the bottom-up approach, the recovery starts at the bottom (lowest) layer where the failure is detected. Higher layer restoration is activated for the traffic, which cannot be restored by lower layer. This can achieve fast recovery at much coarser granularity. Timers are used to activate different layer protection and restoration schemes.

3.4.3 INTEGRATED STRATEGY

The integrated strategy is based on a single integrated multi-layer recovery scheme. This recovery scheme has a full knowledge of all the network layers and it can decide about the recovery action i.e. when and which layer (or layers) is activated to start the recovery process. A good example of this scheme is given in [30]. In this integrated scheme, GMPLS (Generalized Multi-Protocol Label Switching) control plane is used to combine the network state information from both IP and WDM layers. This scheme dynamically allocates restorable bandwidth guaranteed paths in IP over WDM networks against optical link/node failures. It has been shown that integrated schemes improve the network performance. The integrated approach is most flexible one but at the cost of increased complexity due to requirement of intelligence in the network.

3.5 CONCLUSIONS

Several protection and restoration schemes have been reviewed in this chapter. In optical layer protection schemes, the path protection schemes provide better resource utilization at the cost of more restoration time and computational complexity, whereas link protection schemes can provide fast restoration and capacity can be provisioned once and for all. However, resource utilization will be the issue in link protection schemes. Path segment protection concept came as a result of combining best of path and link protection schemes. *p*-Cycles, a span protection technique have addressed the issue of resource efficiency and improved the resource utilization using protection of straddling link failures also. Due to their pre-connected structures, fast restoration is inherent property of *p*-cycles. Thus, *p*-cycles may be one of the promising schemes for optical layer protection.

Optical layer protection schemes provide protection at the fiber level i.e. coarser granularity. All the lightpaths (thousands of connections at higher layers) in a single fiber can be protected simultaneously in fiber level protection schemes. However higher layer node (IP router) failures cannot be recovered in optical level protection. Higher layer restoration schemes take care of failure in IP and higher layers. Use of higher layer to recover the failures of lower layer like fiber cuts, is not advisable due to fault multiplication problem i.e. a single fiber cut result in the failure of thousands of connections at higher layer.

The integrated schemes can be used to combine the best of optical layer and higher layer protection and restoration schemes. The physical level failures are to be recovered in the optical layer schemes to avoid the severe problem of fault multiplication towards the higher layers. Along with this, higher layer schemes can be used to recover higher layer node (IP router) failures or single link failures in the higher layers.

CHAPTER 4
P-CYCLES

p-Cycles are the results of efforts to provide restoration in the mesh topology at high speed comparable with the restoration speed provided by automatic protection switching in SONET networks which uses ring topology. In the following sections, first a brief review of the ring protection in SONET networks is presented and then *p*-cycles are discussed.

4.1 RING PROTECTION IN SONET

Most of the SONET networks are connected in the form of rings. In these networks the protection is provided by self healing rings using automatic protection switching (APS) protocol. With point to point links of SONET, the APS is used to provide 1+1, 1:1 and 1:N protections. These schemes are same as discussed in the section 3.2.1. The APS protocol is used to send the failure and switching information to the upstream node.

In point to point links, with 1+1, no protocol is needed as signals are transmitted simultaneously on two different channels and as soon as the loss of light or signal degradation is sensed the receiver simply switches over to the other channel. With 1:1, as per the simple APS protocol, when any node detects the loss of light or link failure, it stops transmitting on the working channel and switches over to the backup channel for transmission [22]. With this method, the other node also need to become aware of the failure, and will switch over to the backup channel. In case of 1:N, after the detection of failure, as per the APS protocol, the receiving node looks for the back up channel. If the backup channel is available, the node sends the identification of the failed channel on the spare channel. The other node confirms back the identification of the failed channel on the spare channel, and then the transmission starts on the backup channel [37]. The above is needed because for N channels, there is single backup channel.

SONET rings are the extension of point to point APS. For these rings the recovery time required is less than 60 ms. This time includes failure detection, switching time, propagation delay in ring and re-synchronization. These are called Self-Healing rings as the failure detection and switching to protection fiber is done automatically using APS. There are two types of SONET rings which are most widely used –unidirectional path switched rings (UPSR) and bi-directional line switched rings (BLSR) [32]. As the name suggests UPSR works at the path level and BLSR works at the line level.

4.1.1 UNIDIRECTIONAL PATH SWITCHED RINGS

With ring topology, unidirectional path switched ring (UPSR) provides 1+1 protection. As shown in Figure 4.1, two fibers are used, one as working fiber and the other as protection fiber. The traffic is transmitted simultaneously on both the fibers (in clockwise direction on the working fiber and in anticlockwise direction on the protection fiber).

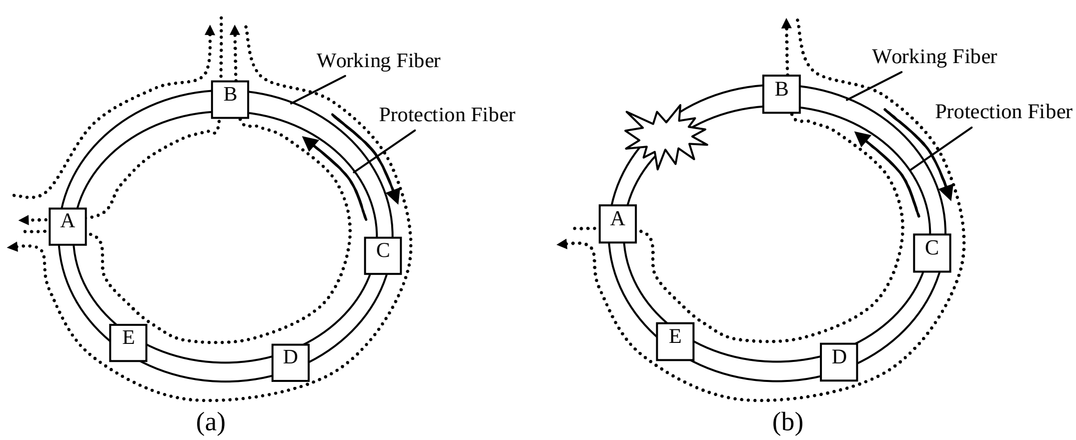

Figure 4-1 Working of a UPSR, (a) before failure, and (b) after failure

The receiver monitors both the paths and the differentiation between working and protection is arbitrary. In case of failure or signal degradation, the receiver simply switches to the other path. The monitoring is done on path to path basis and switching is performed for a path, not for the entire line. The restoration is very fast as it requires no signaling. However, fast restoration is achieved at the cost of resource efficiency. As the traffic flows only in one direction, the path lengths are obviously large for some nodes in the ring topology [22], [32], [37]. A more efficient method is BLSR, which is discussed in the next section.

4.1.2 BI-DIRECTIONAL LINE SWITCHED RINGS

BLSR is based on 1:1 APS. It has two variants, two fiber (BLSR/2) and four fiber (BLSR/4) rings. The traffic flows in both directions in the BLSR. It requires some amount of signaling and it is rather 1:N APS in terms of signaling, as both nodes adjacent to failure need some coordination and signaling before switching over to protection resources. The SONET uses line-level K1, K2 bytes in SONET frame to perform signaling. Four bits in K1 and K2 are reserved for destination node ID and for source node ID respectively. Hence, maximum number of nodes in a BLSR can be only 16. BLSR rings perform switching at the line-level, and in the event of failure, entire traffic of the span is switched over to the protection fiber. One of the advantages of BLSR is that the capacity reserved for protection can be used to carry low priority traffic which can be pre-empted in case of failure.

- ***BLSR/2***

In this case, there are only two fibers, and working traffic is flowing in both of them through shortest path in opposite directions as shown in Figure 4.2. Equal amount of capacity is used for working and protection in both the fibers. The protection capacity of one is to be used for the working traffic in opposite direction of the other fiber. Ring switching is used with BLSR/2 rings to restore the connection after failure. The working traffic of the failed span is loop backed into the protection capacity of the other fiber carrying traffic in opposite direction [22], [32], [37].

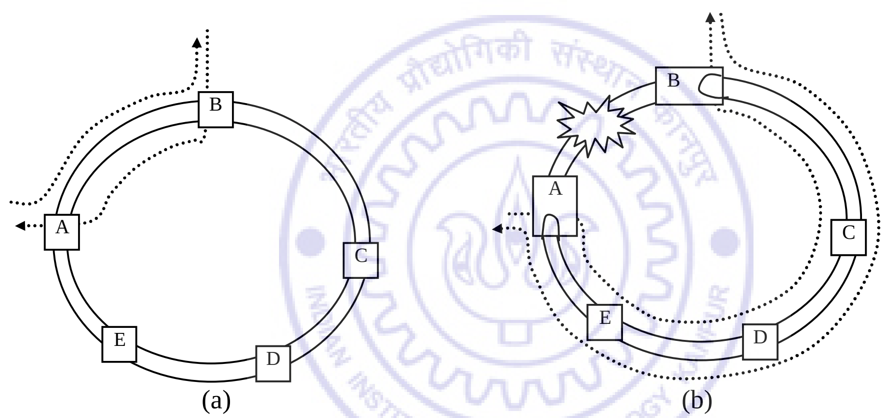

Figure 4-2 Working of a BLSR/2 Ring, (a) before failure, and (b) after failure

- ***BLSR/4***

In BLSR/4 there are four fibers instead of two in BLSR/2. Two fibers are used to carry working traffic, one in clockwise and other in anti-clockwise direction as per the shortest path. Remaining two fibers are used to provide protection to the two working fibers. Ring switching is performed in the same manner as in BLSR/2; in the event of failure, the traffic of the working fibers are switched to the two separate protection fibers. With BLSR/4, span switching is also feasible. Span switching can be performed if a transmitter or receiver of the working fiber fails, then traffic can be switched over to the same span of protection fibers as shown in Fig. 4.3. Span switching cannot be used if there is fiber cut, because the protection fibers usually are not routed separately from the working fibers. In the event of fiber cut, ring switching is often used.

Just double bandwidth is available with BLSR/4 than BLSR/2, and BLSR/4 can handle more failures than BLSR/2 due to span switching. However, ring management is more complicated in BLSR/4 [22], [32], [37].

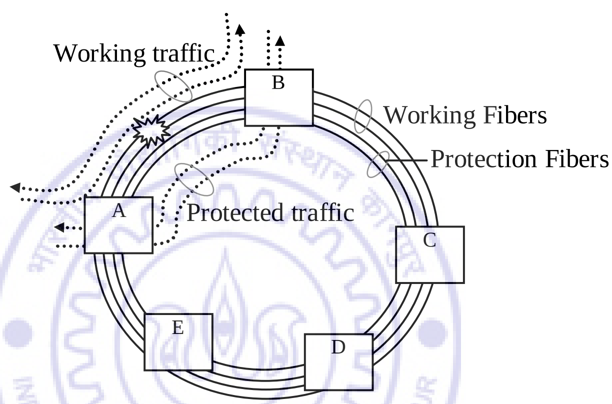

Figure 4-3 Span Protection in BLSR/4

4.2 *P*-CYCLES

The restoration time less than 50 ms is required property of self-healing rings of SONET. In the ring structure, after the detection of failure and signaling, only two switching actions are required at the adjacent nodes of the failed span to restore the traffic. Such a fast restoration can be provided with 1+1 path protection in case of mesh networks. However, this requires a lot of spare capacity, or in other words it is not capacity efficient. For the mesh networks the problem has been solved with *p*-cycles, which were first reported by Prof Wayne D. Grover, Demetrios Stamatelakis and group [81].

It is very interesting to know that at the time of invention of *p*-cycles, inventors themselves could not believe the achievable capacity efficiency of the *p*-cycles. Initially, they thought that the capacity efficiency is due to some 'mistake' [37]. When they could not find any error, then with the help of "Clamshell" diagram (spare and protected working capacities are shown in two different planes), they could find that the reason for capacity efficiency is straddling links on which two units of working capacity can be protected [64]. This feature is not available with ring protection, and this is the key feature to provide mesh like efficiency. Thus, for straddling spans no spare capacity is required to form the *p*-cycle, and two units of working capacity on straddling spans can be provided protection as shown earlier in Fig 3.9. Further, the *p*-cycles provide 1:N shared protection like BLSR, to all the on-cycle spans. The second feature, of ring like speed is attributed to pre-configuration of *p*-cycles again like BLSR rings.

4.2.1 P-CYCLE FORMATION METHODS

On the basis of work reported in the literature, the methods for the formation of *p*-cycles can be categorized in many ways. One of the categorizations may be based upon the computation method, i.e. the *p*-cycles can be formed in a centralized way or they can be formed in a distributed manner. The other categorization may be based upon the order of *p*-cycle formation and routing of working demands. The *p*-cycles can be formed after routing of working demands or jointly with working demands, or first *p*-cycles are formed and then demands are routed as per the available protection capacity. Further classification may be based upon the method used for optimization. For the optimization, ILP, genetic algorithms, Swarm Intelligence or some other heuristics can be used. The classification covering all the above aspects is shown in Fig 4.4.

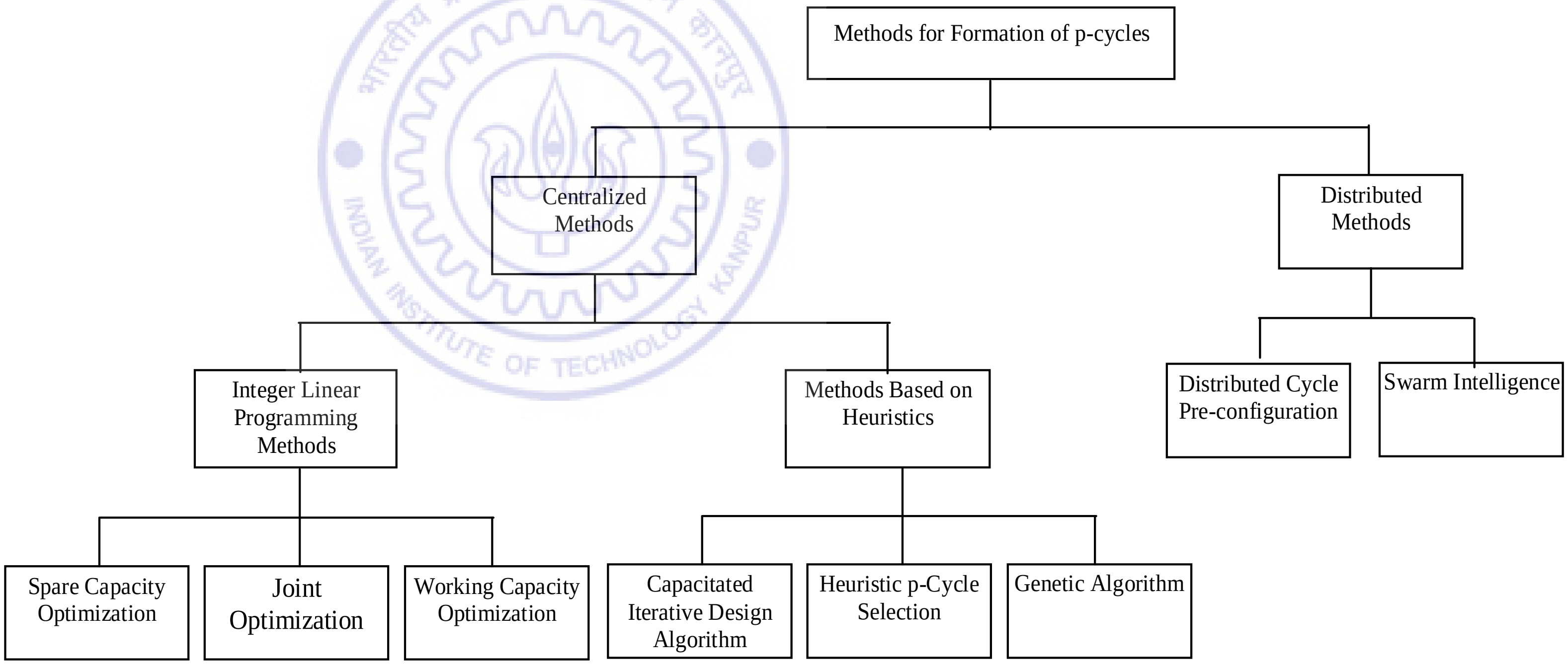

Figure 4-4 Classification of the *p*-cycle formation methods

- ***Centralized Methods***

In this method, a set of *p*-cycles is found from all the possible cycles of the network graph, to protect all the working capacities on the spans. There are various methods discussed below to perform this operation.

i. Integer Linear Programming Models

Three different models have been used for optimization. In the first model, only spare capacity is optimized, second model is for joint capacity optimization where working and spare both the capacities are optimized jointly. In the third model, concept of protected working capacity envelope (PWCE) has been used. First, the protection capacity in the form of *p*-cycles is found and then the demands are routed in such a way that they are protected.

- **Spare Capacity Optimization (SCO)**

In this approach, all the cycles of the network graph are found in advance using search techniques [32]. The working paths are found with any suitable algorithm as per the traffic matrix. Then from all the cycles of the network a set of *p*-cycles is selected, using an optimization model, to protect all the working capacities on the spans of the network. This problem falls in the class of NP-hard problems [82], however, this is usually formulated as ILP problem. The ILP model for the above is relatively simple and can be solved very quickly. The optimization objective is to minimize the capacity required for the formation of *p*-cycles [83]. The *p*-cycles obtained by this model have been called span *p*-cycles [66]. Most of the study of *p*-cycles is based on this method. The basic model as used in [83], is given below.

Sets:

W_i Set of working paths passing through failed span i indexed by r.

S Set of spans, indexed by j .

P Set of p-cycles indexed by p .

Parameters:

c_j Cost of span j (assumed to be one throughout the present work).

w_j Working capacity on span j .

π_j^p Equal to 1 if p-cycle p crosses span j , 0 otherwise.

x_j^p Equal to 1 if the p-cycle p protects span j as on cycle span, equal to 2 if p-cycle p protects span j as straddling span and 0 otherwise.

Variables:

sp_j Spare capacity required on span j .

n^p Number of unit-capacity copies of p-cycle p in the solution.

$$\text{Minimize: } \sum_{\forall j \in S} c_j sp_j \tag{4.1}$$

Subject to:

$$w_j \le \sum_{\forall p \in P} (x_j^p . n^p) \qquad \forall j \in S \tag{4.2}$$

$$sp_j = \sum_{\forall p \in P} \pi_j^p . n^p \qquad \forall j \in S \tag{4.3}$$

$$n^p \ge 0 \qquad \forall p \in P \tag{4.4}$$

Equation (4.1), objective function minimizes the total spare capacity used to form the p-cycles. Equation (4.2) ensures that all the working capacity of every span is protected for

100% protection for single failures. Equation (4.3) provides sufficient spare capacity on every span to form the *p*-cycles.

Based on this model, the set of *p*-cycles have been found with various other constraints also. In [66], [84] the flow *p*-cycles have been found to protect the path segment with this method but with a separate set of constraints. The complete path protection with *p*-cycles has also been determined using ILP model [58], [59], [85]. To restrict the restored path length, hop limited and circumference limited *p*-cycles have also been found with an ILP model [86]. In this case, there is an additional constraint which restricts the protection path length by the hop limit. Because of this constraint, the minimum capacity required for the formation of *p*-cycles is relatively higher in this case. Shared *p*-cycles have also been reported for the protection of WDM networks [87]. The set of shared *p*-cycles has been found with the same objective function but with some more constraints. In [88], with the help of ILP model, *p*-cycles have been found to provide protection against single SRLG failure. The ILP model has also been used to find the *p*-cycles such that end to end unavailability of the restored path remains within the unavailability bound required by the user [89].

The total number of cycles in a large network with high degree of connectivity will be quite large. Various heuristic algorithms are available [90]-[95] for pre-selection of appropriate *p*-cycles from all possible cycles of the network to reduce the size of the set of candidate *p*-cycles. This reduces the solution time of ILP.

- **Joint Capacity Optimization (JCO)**

In the first model, only the spare capacity is optimized with the constraints of protecting all the working capacity of every span. The second model provides the optimization of total capacity i.e. spare plus working. The demands are not routed in advance to find the working capacity, instead the set of working routes are found for each source-destination pair. From the set, the working paths for each source-destination pair are selected along with the placement of spare capacity to optimize the total capacity [37], [96]. The model [37] is given below.

The additional variables and parameters over and above the ones used in SCO, are given below

Sets:

D Set of demand pairs having non zero demand indexed by t,

E^t Set of eligible working routes for demand pair t, indexed by e

Parameters:

d^t The values of demand for each demand pair t (integer).

$f^{t,e}$ Demand units for t^{th} demand assigned to the e^{th} eligible route (integer).

$\lambda_j^{t,e}$ Equal to 1 if the e^{th} working route for the t^{th} demand passes through span j, 0 otherwise.

Variables:

w_j Working capacity on span j.

$$\text{Minimize: } \sum_{\forall j \in S} c_j (w_j + sp_j) \tag{4.5}$$

Subject to:

$$d^t = \sum_{\forall e \in E} f^{t,e} \qquad \forall t \in D \tag{4.6}$$

$$w_j = \sum_{\forall t \in D} \sum_{\forall e \in E} f^{t,e} . \lambda_j^{t,e} \qquad \forall j \in S \tag{4.7}$$

$$s_j = \sum_{\forall p \in P} \pi_j^p . n^p \qquad \forall j \in S \qquad (4.8)$$

$$w_j \le \sum_{\forall p \in P} x_j^p . n^p \qquad \forall j \in S \qquad (4.9)$$

$$n^p \ge 0, \qquad \forall p \in P \qquad (4.10)$$

$$s_j \ge 0, \quad w_j \ge 0 \qquad \forall j \in S \qquad (4.11)$$

The objective function Equation (4.5) minimizes the cost weighted total capacity required for routing of working paths and for providing protection. Constraint (4.6) ensures that all the demands are routed, and constraint (4.7) gives the amount of working capacity on a span. Equation (4.8) provides sufficient spare capacity on a span required by all the *p*-cycles of the solution set. Constraint (4.9) ensures that protection provided by all the *p*-cycles of the solution set is sufficient to protect all the working capacity of the span. The results of SCO and JCO have been compared in [96]. The comparison clearly establishes the superiority of JCO with respect to capacity requirement. However, the solution time is much more in case of JCO as compared to only spare capacity optimization in SCO.

JCO has also been used to optimize the capacity without using all possible cycles of the network [97]. It can select only from the fundamental cycles that have no straddling links. The non-simple cycles[3] have also been considered in the solution. However, this approach is suitable only for planar networks. With non-simple *p*-cycles, the model outperforms the simple cycle ILP models. The advantage of non-simple *p*-cycles in terms of capacity, over simple *p*-cycles has also been shown in [98]. Again the problem has been formulated as JCO.

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[3] The cycle which passes through a node or a span twice, is known as non-simple cycle.

- **Working Capacity Optimization**

In this model, the *p*-cycles for protection are found first and then the working paths are routed within the protection domain. The concept is known as protected working capacity envelope (PWCE). The objective is to maximize the working capacity which is protected with the set of *p*-cycles found in the ILP model. There can be many problem formulations depending upon the type of inputs given. The total capacity of each span may be given, or only the spare capacity of each span may be given. These cases have been extensively explored in [99]. The model is given below, for the case in which spare capacity of each span is given to begin with.

Maximize: $\sum_{\forall j \in S} w_j$

Subject to:

$$w_j \leq \sum_{\forall p \in P} (x_j^p . n^p) \qquad \forall j \in S \tag{4.12}$$

$$sp_j \geq \sum_{\forall p \in P} \pi_j^p . n^p \qquad \forall j \in S \tag{4.13}$$

If total capacity of the spans is given, then the constraint given below, is also added

$$T_j \geq w_j + sp_j \qquad \forall j \in S \tag{4.14}$$

where T_j is the total capacity of span j.

PWCE concept has also been used for dynamic traffic. The incoming requests are routed in the available capacity which is protected [100], [101]. The nature of dynamic traffic is random. The connection requests arrive and depart randomly. To provide optimization to the dynamic traffic scenario, the adaptive PWCE (APWCE) has been proposed in [102]. The APWCE slowly adapts to the changing traffic scenario with reoptimization process using ILP based on the previous envelope. The objective is to provide protection to as many demands as possible within the available capacity constraints.

Lot of work is available in the literature, based on ILP methods, basically to optimize the capacity, spare or working or both. Solutions are available for static as well as dynamic traffic scenarios. They can be solved with ILP models very quickly only for small networks and are very useful to perform in depth studies and to gain insight in the *p*-cycle techniques. The actual networks are usually much larger. Nevertheless, *p*-cycle techniques can be applied with many heuristics algorithms which are discussed in the next section.

ii. Methods Based on Heuristics

The heuristic algorithms provide solutions in a much smaller time at the cost of reduced capacity efficiency as compared to the ILP models. However, the solutions are usually very close to optimum values.

- **Capacitated Iterative Design Algorithm (CIDA) [103]**

The heuristic uses straddling link algorithm (SLA) [90] to find the set of candidate *p*-cycles with a single straddling link and then large cycles are formed by 'add', 'join', 'expand' and 'grow' operations. Then the set of *p*-cycles to protect all the working capacities of the spans are found using CIDA. The actual efficiency of a *p*-cycle is defined as

$$AE(p) = \frac{\sum_{\forall j \in S} w_j . x_j^p}{\sum_{\forall j \in S | x_j^p = 1} c_j} \tag{4.15}$$

Here, w_j is the unprotected capacity left on the span *j* at the time of calculation of actual efficiency. The term in the denominator of the right hand side gives the total cost of the *p*-

cycle. The actual efficiency of every *p*-cycle in the set of candidate *p*-cycles is calculated as per the current working capacity values. The best score *p*-cycle is selected and the traffic protected by this *p*-cycle is subtracted from the existing values of the working capacity. The process is repeated until all the working capacity is protected. The CIDA-grow algorithm performs best and requires just 5.9% more capacity than the ILP model [103].

The work in [104] is almost similar to the heuristic discussed above. However, for finding the set of candidate *p*-cycles, the algorithm given in [105] has been used, after that CIDA is used to select the final set of *p*-cycles.

- **Heuristic *p*-Cycle Selection (HPS) and Refine Selected Cycles (RSC) [106]**

The set of candidate *p*-cycles is selected using modified version of SLA. With the modified version, all the cycles of the network are selected by finding K shortest path between two nodes of all the spans. By joining two such paths, a cycle is formed and then by increasing the number K, all the cycles of the network can be found.

The HPS selects the *p*-cycle on the basis of cycle weight, the waste capacity, the effective straddling span factor, and the actual protection capacity. The cycles which are passing through the spans having zero spare capacity are removed before every search. The cycle weight is defined as the ratio of the total actual protected capacity with the power *n* (a control parameter) to the total spare capacity required.

If a cycle is passing through a span with zero working capacity, then the cycle is not protecting any on-cycle capacity and the capacity used by the cycle is considered as waste. The waste capacity of the cycle is found by adding the waste capacity of all the spans of the cycle. Thus a cycle with a lower value of waste capacity is better.

Similarly, the effective straddling span factor is calculated by finding the actual capacity protected by the cycle on all of its straddling spans. The actual protection capacity is the total of actual capacity protected by the *p*-cycle (on a straddling span *p*-cycle can protect two units of capacity, however, there may be only one unit of unprotected working capacity on that span, then the actual protection capacity will be one for that span).

The cycles are compared on the basis of the above four factors and the best cycle is selected. The search is repeated till all the working capacity is protected.

The set of selected cycles is again refined using RSC. Two or more *p*-cycles are replaced with a single *p*-cycle if the total protection capacity remains the same with smaller amount of spare capacity used by new *p*-cycle.

- **Genetic Algorithm [107]**

The genetic algorithm has been used with general heuristic search technique. In this work a priori efficiency $APE(p)$ of a *p*-cycle is defined as

$$APE(p) = \frac{\sum_{\forall j \in S} x_j^p}{\sum_{\forall j \in S | x_j^p = 1} c_j} \quad (4.16)$$

The actual network protection capacity ANPE is defined as the ratio of total working capacity of the network to the total spare capacity used by the *p*-cycles to protect all the working capacity in the network.

The ANPE is used as the goal function. A set of 'top-ranked' *p*-cycles are selected from the set of all the cycles of the network based on their a priori efficiency. With the optimization process of the genetic algorithm, the optimization variable n^p (number of copies of *p*-cycle *p*, it may be 0 also) for top-ranked *p*-cycles is calculated (for more details the reader is referred to [107]). This will give the required spare capacity in the network and then goal function can be calculated. The quality of a given solution is obtained by the goal function which directs the process of searching optimal solutions. However, the results of genetic algorithm have not been compared with ILP or any other heuristic in literature.

- ***DISTRIBUTED METHODS***

The above algorithms are centralized techniques. However, in the second category i.e. distributed algorithms, only two methods are available –DCPC and Swarm Intelligence based on ant like agents.

i. DCPC [108]

In this method the *p*-cycles are searched and pre-configured in the spare capacity with DCPC (Distributed cycle Pre-Configuration) protocol. Again the working paths are established with a suitable algorithm as per the traffic matrix, then the *p*-cycles are formed in totally distributed manner using DCPC in the remaining capacity of the network. As shown in [108], this method is very near to optimum solution. In this method, a self-organizing strategy for the autonomous deployment of *p*-cycles has been developed. With this strategy, the set of the *p*-cycles continuously modify themselves with changes in the working capacities, to remain optimum. It has all the advantages of distributed protocols.

This protocol can be implemented in any real network for the deployment of *p*-cycles with optimality. The DCPC protocol builds up on the statelet broadcasting. The statelets are information bearing packets with some defined fields. The broadcast rules of the statelets are based on the self-healing network (SHN) protocol given in [109]. The algorithm runs in the background without affecting the routing of working paths and *p*-cycles are formed in advance of any failure. However, only one *p*-cycle is obtained in one iteration of the algorithm, even if there exits multiple copies of the same *p*-cycle.

ii. Swarm Intelligence System [110]

Swarm intelligence helps in enabling the distributed, adaptable and self organized network management operations. These systems are based on 'emergent behavior' and are inspired by biological systems. The system consists of simple and similar autonomous mobile or ant like agents which communicates with each other asynchronously. The management information is disseminated through these agents whose behavior is similar to those of ants. The operation of these agents is almost independent. The *p*-cycle ant system used in [110] is based on cross entropy Ants (CE-Ants). The details on cross entropy are available in [111]. The communication between agents takes place with the messages they leave or gather at nodes they visit. The aggregation of messages forms the basis for the formation of *p*-cycles. The *p*-cycle search and the traffic switch over to a *p*-cycle may be performed online in a fully distributed manner.

The swarm intelligence systems are also fully distributed with high redundancy and adaptability. They can be used to find near optimal solutions to NP hard problems. Details of these systems are out of the scope of the present work. The interested reader may refer to [112] for more information on the subject.

4.2.2 CAPACITY OF P-CYCLES

A lot of literature is available on the capacity efficiency of *p*-cycles [37], [83], [113], [114]. The redundancy is defined as the ratio of spare to working capacity and capacity efficiency is reciprocal of redundancy [37]. It has been proved in [113] that in the limiting case when *p*-cycle passes through all the nodes of the network, the redundancy with *p*-cycle has the same well known lower limit of $1/(\overline{d}-1)$ as that for a span restorable mesh network (where, $\overline{d}=2S/n$, S and n are total number of spans and nodes in the network respectively). It has been suggested that the Hamiltonian *p*-cycles may be the good *p*-cycles in terms of efficiency [113].

In [115], [116], it has been shown that the best *p*-cycle efficiency can be obtained with 'flat mesh networks' where the capacities of all the spans are identical. In [116], the redundancy for the homogeneous network (where all the spans have equal working capacity) is shown to be $2/\bar{d}$. This is somehow smaller than the lower bound shown in [113]. This is due to the fact that in homogeneous networks the total protection capacity of a *p*-cycle could not be exploited. The unique feature of straddling span protection of *p*-cycles is lost. The double protection on straddling spans could not be utilized as on every span the working capacity is same. For semi-homogeneous networks the working capacities are double on straddling spans as compared to on-cycle spans. Then the lower limit of $1/(\bar{d}-1)$ can actually be achieved with Hamiltonian *p*-cycles.

D.A. Schupke has derived the condition in which only the Hamiltonian *p*-cycle can achieve the lower bound of efficiency [117]. However, the derivation has been proved wrong by P. Cholda in [118].

ILP solutions have also shown that most of the *p*-cycles of the solution set are Hamiltonian or near Hamiltonian (just a node less than the total number of nodes in the network) and some of them are small. The selection of small cycle in the optimum solution is due to the local concentration of the traffic. The traffic density between the nodes of a small *p*-cycle is more as compared to the nodes of a large *p*-cycle [114].

The high efficiency of *p*-cycles can be attributed to the fact that a *p*-cycle can provide protection to all the on-cycle as well as straddling spans simultaneously. In this, the capacity used to form the *p*-cycle has been shared to provide protection to all the on-cycle and straddling spans. We can say that *p*-cycles are a form of shared span protection and it can be given the name shared backup span protection i.e. **SBSP**.

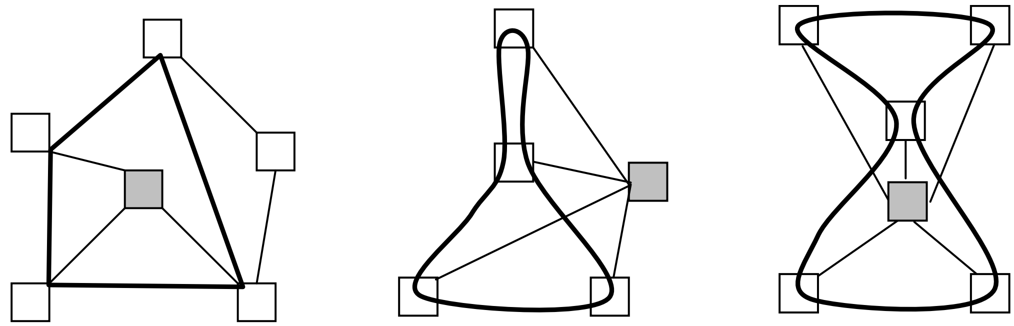
4.2.3 TYPES OF PROTECTION

Initially *p*-cycles were invented and used for link or span protection. Due to the specific advantage of capacity efficiency with fast restoration speed, they have been used to provide multiple types of protections. They have been used at various network layers with varying granularity and even for multiple failures.

- ***NODE, PATH AND PATH-SEGMENT PROTECTION***

Apart from providing span protection, *p*-cycles can also provide node protection with the help of node encircling *p*-cycles [77], [119]. The idea was proposed in [77]. There has to be a *p*-cycle which covers all the nodes adjacent to the failed node but not the failed node itself, to protect all the flows which are passing through the failed node. The traffic originating or terminating at the failed node cannot be recovered. The node encircling *p*-cycles may not always be simple and there may be non-simple *p*-cycles also (Fig. 4.5). A network with *n* number of nodes requires *n* *p*-cycles to protect all the nodes with node encircling *p*-cycles. An algorithm to find the node encircling *p*-cycles is given in [119]. The algorithm is called node-encircling *p*-cycles mining algorithm (NCMA).

The above network model with one *p*-cycle to protect a node is not capacity efficient as shown in [120]. Two more network models have been developed with the help of ILP and shared node-encircling *p*-cycles (NEPC). In one model, both sides of the NEPCs are evenly used to route the protection path, whereas in the other model, the side of the NEPC, to which the protection path is routed, is also determined making it even more capacity efficient.



(a) Simple p-cycle (b) Non-simple p-cycle (c) Non-simple p-cycle

Figure 4-5 Node encircling *p*-cycles

The *p*-cycle technique has also proved to be successful for complete path protection with failure-independent path-protecting (FIPP) *p*-cycles [58], [59]. The idea is to have a common *p*-cycle for all the paths which are mutually disjoint and having end nodes on the *p*-cycle. Path protecting *p*-cycles offer all the advantages of SBPP and in addition the protection path is pre-configured also. Real time switching is only required at the end nodes of the failed path. However, some signaling is required, as in any other path protecting scheme except 1+1 APS, between the end nodes to perform the switching. If the working paths are node disjoint also, then node protection is also provided with path protecting *p*-cycles. A fast method to design the FIPP network based on disjoint route set using ILP and a heuristic to reduce the set of candidate *p*-cycles for the final set is given in [85].

Flow *p*-cycles have been used to protect path segments [66]. The flow *p*-cycle can protect the flows crossing the *p*-cycle. The flows can also pass through the nodes which themselves are not parts of the *p*-cycles in between these two crossing points. Flow *p*-cycles can also provide path protection, node protection and the usual span protection. It has been shown that only a very small additional capacity is required to provide 100% node and span failure [66].

However, the speed of the *p*-cycle is compromised in these scenarios as some signaling is required between the nodes which lie on the *p*-cycle as well as on the flow path. More complexity is involved in finding the node-encircling, FIPP, and flow *p*-cycles as compared to span protecting *p*-cycles. Further, methods of finding these *p*-cycles falls under the centralized category, whereas span protecting *p*-cycles can be found in distributed manner also [108], [110].

- ***PROTECTION AT VARIOUS LAYERS***

Theoretically *p*-cycles can be used to provide protection at any connection-oriented transport layer [83]. The protection can be provided at IP layer [77], and in SONET networks [83], [108]. In MPLS networks also *p*-cycles can be used to provide protection with bandwidth efficiency [120].

However, most of the work on *p*-cycles is related to WDM or DWDM optical network protection [84], [87], [90], [100], [101], [104], [114], [119], [122]-[126]. In these networks, usually the protection is provided at the level of wavelength, where one unit corresponds to one wavelength. If the same wavelength is used by a path on all the links, then the path is said to be a wavelength path (WP) and the constraint is called wavelength continuity constraint. On the other hand if wavelength converters are available at every node of a path and the path can have any free wavelength on any link then the path is called virtual wavelength path (VWP) and the network is known to be fully convertible [37].

The ILP formulation for WP case is given in [123]. One more dimension of wavelength is added to the spare capacity optimization case discussed in centralized methods (section

4.2.2). The ILP for VWP case is similar to spare capacity optimization case. A heuristic has been given for wavelength assignment and *p*-cycle search (PCS) in [124]. The WP and VWP are the two extreme cases, one without any wavelength converter and other fully wavelength convertible nodes, i.e. at every node any wavelength can be converted to any other wavelength. The networks with a few wavelength converters have been discussed in [125], [126]. It has been shown in [125] that with a small increase in spare capacity, number of wavelength converters can be reduced significantly. The wavelength converters are placed at the points where WP *p*-cycles are accessed.

- ***PROTECTION TO MULTIPLE FAILURES***

Many strategies have been proposed in literature to provide dual or multi failure network survivability. Survivability in dual failures with static[4] *p*-cycles has been provided with ILP formulation in [127]. Survivability in multiple failures is again provided with static *p*-cycles in [128], assuming that only one failure occurs in one *p*-cycle, and in [129] multi failure survivability (MFS) scheme has been used to provide survivability handling one failure at a time. The results show that networks with higher $\bar{d}$ has higher survival chances to second failure as compared to networks with lower $\bar{d}$.

The study in [130] shows that with reconfigurable *p*-cycles, the dual failure restorability enhances. In this study, after the restoration of the first failure, the *p*-cycles are reconfigured either a) completely or b) incrementally. In the complete reconfiguration, the *p*-cycles are reconfigured in the spare capacity dynamically, and a new set of optimum *p*-cycles is found to protect second failure. While in case of incremental configuration, the old

[4] The same set of p-cycles which are used for single failure protection, has also been used for dual protection.

p-cycles are retained and some new *p*-cycles are deployed to protect second failure. The study in [131] compares the reconfiguration method of *p*-cycle with two step dynamic repair of *p*-cycle. Two effects are observed on the *p*-cycle, first the failed span and second the path provided to protect the working traffic. In the dynamic repair method, to repair the effected *p*-cycle, either an alternate path is found to free the capacity used by protection path provided by *p*-cycle or another alternate path is found to replace the failed span. The dynamic repair method has been found to be more efficient in terms of spare capacity utilization as compared to incremental configuration method. However, complete reconfiguration of *p*-cycles after the first failure is the most efficient method.

Differentiated services has been provided with *p*-cycles using ILP formulation in [132]. Here again, the dual failure survivability is provided to the platinum traffic. It has also been shown that within the same resources of single failure survivability, *p*-cycles can provide dual protection to as much as 30% of all demands in the test cases.

- ***PROTECTION TO DYNAMIC TRAFFIC***

Initially the *p*-cycles have been proposed to be formed in the spare capacity, after the routing of working paths have been finalized. However, *p*-cycles can also be used to provide restoration in the dynamic traffic environments. The *p*-cycles are formed in advance and then as per the demands, working paths are routed in such a way that protection is available to the working paths. The issue is how to form the *p*-cycles in advance and how to allocate protection capacity.

In [101], the set of *p*-cycles has been found in such a way that protection could be provided to all the spans, either as on-cycle or straddling span. For on-cycle spans half of the capacity is allocated for protection. The set of *p*-cycles has been found again using ILP model. As the demands arrive, the working paths have been found using some preferred routing scheme. The results show that *p*-cycle based approach provides better restoration than SBPP for networks with higher values of $\overline{d}$ for smaller values of $\overline{d}$ the reverse is true.

In another approach [133], for every span of the network one *p*-cycle is found using either SLA [90] or Grow [103] algorithm as set of candidate *p*-cycles. Initially no *p*-cycle is selected and as per the demand, the working path is routed using shortest path algorithm. To protect the path, *p*-cycle or *p*-cycles are selected from the candidate *p*-cycles. On the arrival of further demands, the priority is to route the working path in the protected capacity available through previously selected *p*-cycles. If any link(s) in the path remains unprotected then more *p*-cycle (s) from the candidate set are selected to protect the link(s).

The concept of PWCE and APWCE (under centralized methods of Section 4.2.2) have also been used in [99], [100], [102] for dynamic traffic environments.

4.2.4 IMPLEMENTATION OF P-CYCLES

The implementation of *p*-cycles in a network is shown in Fig 4.6. A working path through ABC (shown in green colour) is set up from a source node to a destination node. Since we are assuming the network to be bidirectional and symmetric, hence, a reverse path through CBA also exits. There are two *p*-cycles – ADCBA and ABCDA (shown in blue colour) which are pre-configured with the spare capacity to protect the bidirectional working paths (Fig. 4.6(a)).

Let us consider the failure of span AB. The working paths will now be restored with the protection path provided by the *p*-cycles. The working path through ABC and CBA will now be restored through the protection paths ADCB of *p*-cycle ADCBA and BCDA of *p*-cycle ABCDA respectively (Fig. 4.6(b)).

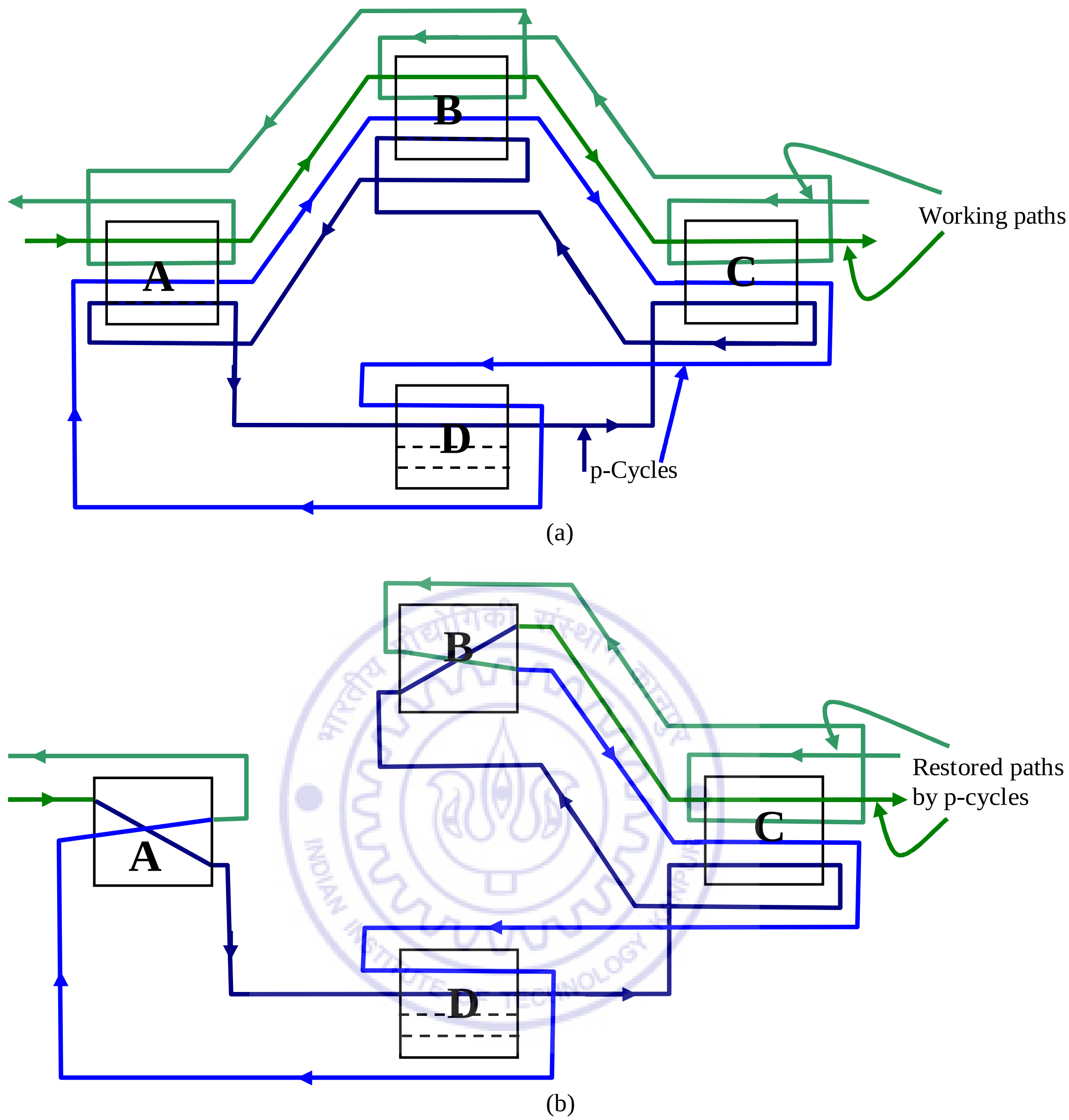


Figure 4-6 Implementation of a *p*-cycle

The ring like speed of *p*-cycle can now be explained. In the event of failure of span AB, two switching actions are performed, first – at node A, to switch the traffic from working path to the *p*-cycle and second – at node B, to switch the traffic from *p*-cycle to the remaining portion of the working path. Similarly, path CBA will also be restored.

In the above example an on-cycle failure has been shown, the straddling span failures can also be restored in the similar manner. In case of straddling spans, *p*-cycles provide two paths. Any one of the two protection paths can be selected for restoration.

4.2.5 RELIABILITY ISSUES

The reliability issue of *p*-cycles has not been discussed much in the literature. However, it has been shown [134] that, with respect to all terminal availability (the availability of *p*-cycle as a whole) the performance of *p*-cycles is inferior to rings, and with respect to two terminal availability (for a path), again for on-cycle spans, the rings performs better; for straddling spans, *p*-cycles have advantage over rings. Further study [135] shows that the mean time to failure (MTTF) is also too low for *p*-cycles and the expected loss of traffic (ELT) i.e. average traffic loss over a year due to failures is quite high. It can be concluded, based on studies in [134], [135], that from reliability point of view the performance of *p*-cycles is somehow inferior. This is largely due to the fact that the length of the *p*-cycles is usually quite large to make them efficient and hence lower reliability.

4.3 SUMMARY

The versatility of *p*-cycles is beyond any doubt. They can provide the advantage of fast restoration of rings along with the capacity efficiency of mesh networks. The reason behind the ring like speed is pre-connection of spare capacity of the network to form the *p*-cycles. The theoretical limit of capacity efficiency of SBPP can be achieved with *p*-cycles because protection to all the on-cycle and straddling spans is provided by a *p*-cycle on shared basis. This protection can also be called shared backup span protection (SBSP).

Various methods are available to design the networks with *p*-cycle protection. The *p*-cycles can be formed either by distributed method in any real network in real time or they can be computed centrally and implemented in a network. Many tradeoffs are available for designing the *p*-cycles e.g. spare capacity vs. length of restored path, computation time vs. heuristics etc.. They can be implemented at various network layers with varying granularity. Almost all types of protection like span, path segment, path and node can be provided with *p*-cycles.

However, reliability of a *p*-cycle is a point to be further considered. The most desirable feature of capacity efficiency can be achieved with span protecting large *p*-cycles. The main issue then is the length of the restored path. The reliability studies show that the not-so-good reliability is due to the long length of the restored path.

Another issue is lack of distributed methods for *p*-cycle formation. Even with DCPC method, only one *p*-cycle can be found in one iteration. In this method, the *p*-cycles are formed off-line before the occurrence of failure, hence, calculation time to find all the cycles, is not so important. However, network load and computational complexities will be high.

The above issues need to be further investigated and the same has been done in this thesis work. The length of the restored path can be reduced with our algorithm for removal of loop backs. The reliability also increases after application of the algorithm. Our work on DCPC reduces computational complexities to a great extent and simplifies the switch implementation. Detailed discussions have been given in the following chapters.

CHAPTER 5
MODIFICATIONS IN DCPC PROTOCOL[5]

This chapter is devoted to the modification in the DCPC protocol for WDM and DWDM optical networks. As a prerequisite to this chapter, the original work on DCPC protocol [108] has been reproduced in Appendix A (with permission from IEEE and the authors). The chapter presents the comparative study performed for statelet forwarding rule, using numpath and then score. After that, the chapter presents the modified DCPC (MDCPC) which reduces the computational complexity by finding all the copies of the same *p*-cycle in a single iteration and all the copies of the same *p*-cycle are aggregated together to take the advantage of possibility of waveband switching.

5.1 DCPC WITH SCORE OR WITH NUMPATH ?

We have compared the statelet forwarding two criterions in this section. It shall be noted that the spare capacity is already provisioned, and DCPC forms the *p*-cycles only with the available spare capacity. At the tandem nodes, in the first case, the statelets are broadcast on the basis of their score[6] values and in the second case the statelets are broadcast on the basis of their numpaths[7] values to form the *p*-cycles. The score is defined as the ratio of numpath and hop counts. The numpath metric gives the units of working

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[5] This chapter is based on the previously published work [136].
[6] A statelet's score is s = (numpaths)/(hopcount).
[7] The numpaths is the number of useful paths that would be provided by a cycle formed from the union of the incoming statelet's route and an imaginary direct span joining the tandem node to the cycler node.

capacities which can be protected and hop count gives the spare capacity used to provide the protection. The test setup used to perform the study is given in the next section.

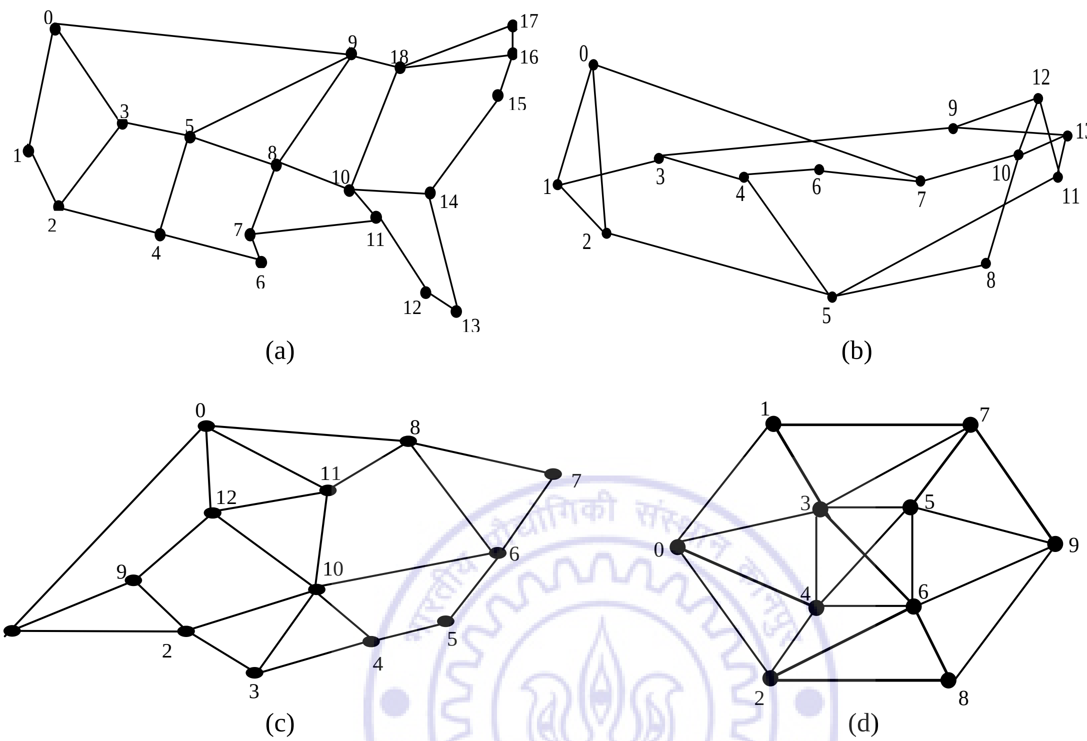

Figure 5-1 Test Networks, (a) Net1, 19 nodes, 28 span, $\overline{d}$ =2.94, and number of eligible cycles=253, (b) Net2, 14 nodes, 21 span, $\overline{d}$ =3.0, number of eligible cycles=139, (c) Net3, 13 nodes, 23 spans, $\overline{d}$ =3.5, number of eligible cycles=410, and (d) Net4, 10 nodes, 22 span, $\overline{d}$ =4.4, number of eligible cycles=833.

5.1.1 TEST SET UP

The test networks Net1, Net3 and Net4 are taken from [22], [82], [108] respectively; Net2 is NSFNET. Net3 and Net4 (SmallNet) have been extensively used in *p*-cycle studies. The test networks used are shown in Fig. 5.1 along with the number of nodes, number of spans, average nodal degree ($\overline{d}$) and number of eligible cycles in the network graph. Fig. 5.2 to Fig. 5.5 show the *p*-cycles in the solution set of SCO (section 4.2.1) model for Net1 to Net4 respectively.

We are assuming that the networks are fully convertible, bi-directional and symmetric. The traffic is assumed to be one unit between each node pair i.e. unit traffic matrix. The routes for the working paths have been found with shortest path Dijkstra's algorithm using hop count as metric for one direction. It has been assumed that corresponding symmetrical network will exist for reverse direction also. The working capacity (w_j) on every span will be equal to the total number of working paths passing through that span (Fig. 5.2 to Fig. 5.5). These initial conditions have been used for all the tests and evaluations unless otherwise stated. A simulator, developed by us in Java has been used to perform the tests and evaluate the performances. The ILP models have been solved with CPLEX 9.0, and input data files are generated with Java codes.

5.1.2 OBSERVATIONS AND DISCUSSIONS

The DCPC with score and numpath has been tested under following three spare capacity (sp_j) conditions.

- Spare capacities provisioned on each span as per the solution of spare capacity optimization model (SCO, case I).
- Spare capacity provisioned on each span as required for link disjoint path protection (LDPP, case II).
- Fixed spare capacity on each spans. The fixed capacity provisioned on each span is equal to the rounded off value of average capacity as per the solution of SCO model (case III).

The observations for Net1, Net2, Net3, and Net4 are shown in Table 5.1. The two metrics score and numpath have been compared on the basis of protected working capacity, used spare capacity and capacity redundancy which is defined as:

η = (spare capacity * 100) / protected working capacity.

In case I, for test network Net3 and Net4 the η values are same. However, for Net1, better η is obtained with numpath metric than with score metric whereas, the vice versa is true for Net2. However, for Net1, with score metric, more number of *p*-cycles are formed and more working capacity is being protected with more spare capacity used by the *p*-cycles as compared to the corresponding values with numpath metric. Thus, with score metric better working capacity protection is available at the cost of more spare capacity consumed. The use of more spare capacity is not an issue here as it has already been provisioned in the network. The vice-versa is true for Net2. However, the differences are very small. On the basis of the above, we can say that the score option is better for Net1 and numpath option is better for Net2. For Net3 and Net4 the above values are same, so any one of the options can be used.

Table 5-1 Comparative study of score vs. numpath based statelet forwarding in DCPC

Test Networks	Total working capacity	Total spare capacity	Total number of *p*-cycles in DCPC		Protected working capacity		Used spare capacity		Capacity redundancy η	
Spare capacity as per SCO (case I)										
			numpath	**score**	**numpath**	**score**	**numpath**	**score**	**numpath**	**score**
Net1	984	754	42	44	878	906	618	650	70.4	71.7
Net2	390	286	22	20	370	362	250	238	67.6	65.7
Net3	316	194	16	16	300	300	170	170	56.7	56.7
Net4	142	70	8	8	142	142	70	70	49.3	49.3
Spare capacity as per LDPP (case II)										
			numpath	**score**	**numpath**	**score**	**numpath**	**score**	**numpath**	**score**
Net1	984	1520	122	124	912	914	1108	1072	121.5	117.3
Net2	390	658	50	56	386	390	530	526	137.3	134.9
Net3	316	458	38	52	302	350	350	366	115.9	104.6
Net4	142	198	22	28	136	136	148	150	108.8	110.3
Fixed Spare capacity (case III)										
			numpath	**score**	**numpath**	**score**	**numpath**	**score**	**numpath**	**score**
Net1	984	840	72	68	888	906	730	726	82.2	80.1
Net2	390	294	22	20	354	348	240	228	67.8	65.5
Net3	316	230	22	22	288	290	206	192	71.5	66.2
Net4	142	88	10	12	122	120	80	80	65.6	66.7

Consider the case II (Table 5.1); in this case, spare capacities are much more as compared to SCO case, because 1:1 path protection is not capacity efficient. The total number of *p*-cycles is higher with score as compared to numpath for all the networks. The score metric provides a better η values and a better working capacity protection for Net1, Net2 and Net3. For Net4, the same amount of protection is available with both metrics but a better η value is obtained with numpath metric. However, in this case the η values are quite high as compared to the same in case I. This is because, in case I, the spare capacity distribution is optimum as per SCO model.

In case III, again the better η values are obtained with score metric for Net1, Net2 and Net3 and for Net4 the better η is obtained with numpath metrics. However, the protected working capacities are more for Net1 and Net3 with score metric and for Net2 and Net4 the vice-versa is true, but the differences are marginal. The η values in this case are better than the same in case II, but the best values are obtained with case I.

The best η values are obtained for all the test networks in Case I as compared to case II and case III because the spare capacity distribution is optimum in case I.

On the basis of above discussions, it can be concluded that for test networks Net1, Net2 and Net3 ($\bar{d} \leq 3.5$) the score metric provides slightly better results in terms of protection capability and capacity redundancy, when large amount of spare capacity is provisioned in the network (case II), and the numpath metric provides better results for Net4 ($\bar{d} = 4.4$). However, the capacity redundancy is very poor for all the test networks in this case as compared to other two cases. When spare capacity is provisioned as per the optimum solution model, with different distributions, then more or less same results are obtained with both score and numpath metrics (case I and case III). Therefore, both the options are equally good and any one of the options can be used.

5.2 MODIFICATIONS IN DCPC

With DCPC, in one iteration, only one copy of a *p*-cycle can be found. This *p*-cycle can protect one link on any one of the on-cycle spans and two links on any one of the straddling spans. If we look at the solutions found with spare capacity optimization model (SCO, section 4.2.1, Centralized methods using ILP), it becomes clear that in the solution set of *p*-cycles, many copies of some of the *p*-cycles exist (Fig 5.2 to Fig. 5.5). It is expected that with DCPC also, many of the *p*-cycles may have multiple copies.

The *p*-cycle can be used in different scenarios, such as; MPLS layer [77], [121] where protection is provided to the label switched paths. In wavelength division multiplexed (WDM) or dense wavelength division multiplexed (DWDM) optical networks, the technique can be used to provide protection to wavelength paths [37], [90], [122], [124]. In all these scenarios, one *p*-cycle can be found with one iteration of DCPC. This happens in all networks using *p*-cycles, including MPLS networks. In case of MPLS networks, it can protect single link on any one of its on cycle spans and two links on any one of its straddling spans. In case of optical WDM or DWDM network, this *p*-cycle can protect one wavelength on any one of its on cycle spans and two wavelengths on any one of its straddling spans.

If more spare capacity is available for more copies of the same *p*-cycle, then to find all of them, the number of iterations required by the DCPC will be equal to the number of copies of the *p*-cycle. The problem becomes more severe in case of heavily loaded or large size networks, where amount of traffic is quite large. Obviously, to provide protection to all the traffic, more spare capacity will be required. Consequently large number of *p*-cycles including many copies of many of the *p*-cycles will be formed with more signaling traffic.

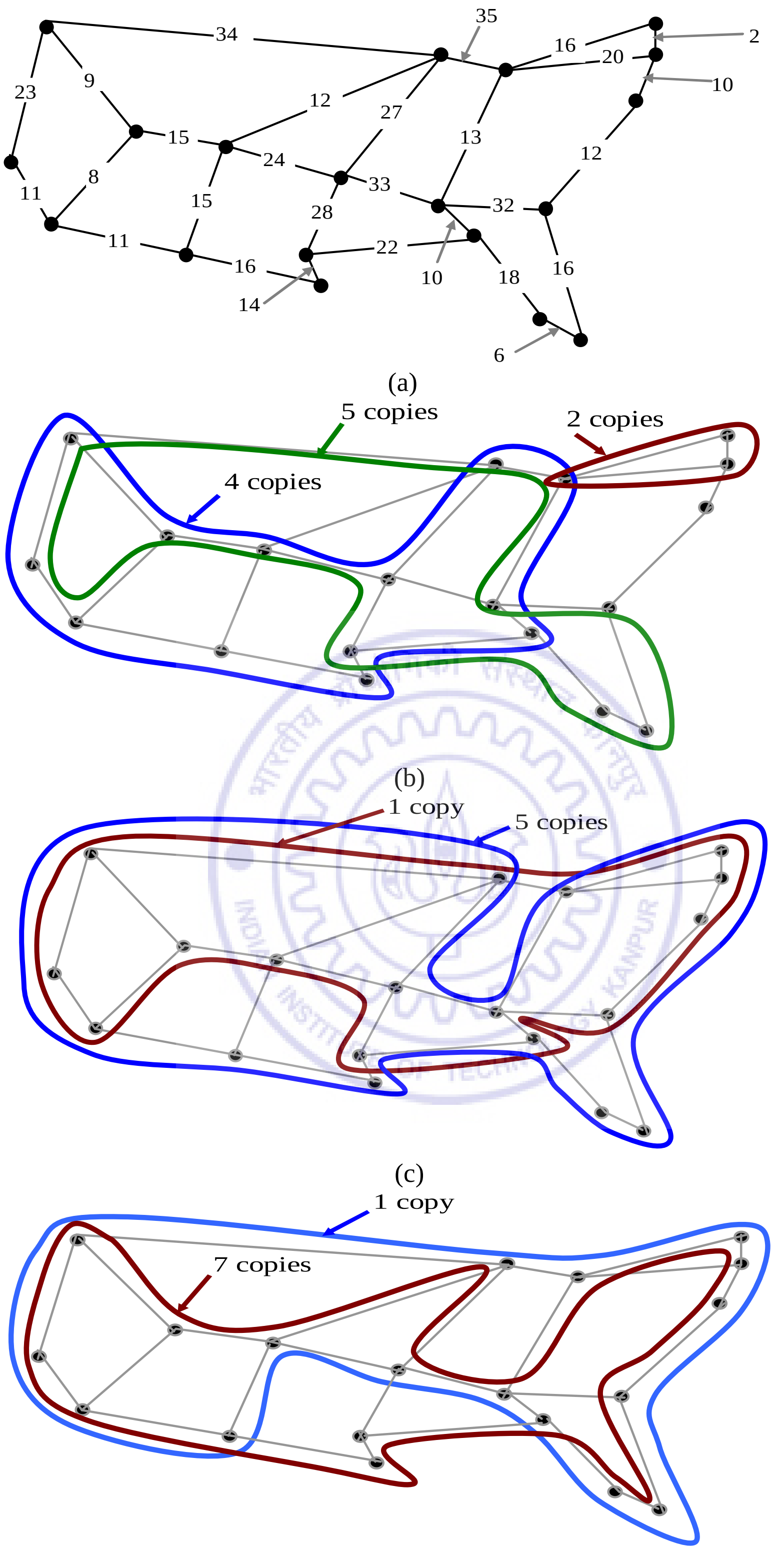

Figure 5-2 **Solution set of SCO model for Net1, (a) Working capacities on each span, (b) to (d) the *p*-cycles with number of copies as obtained with the SCO model**

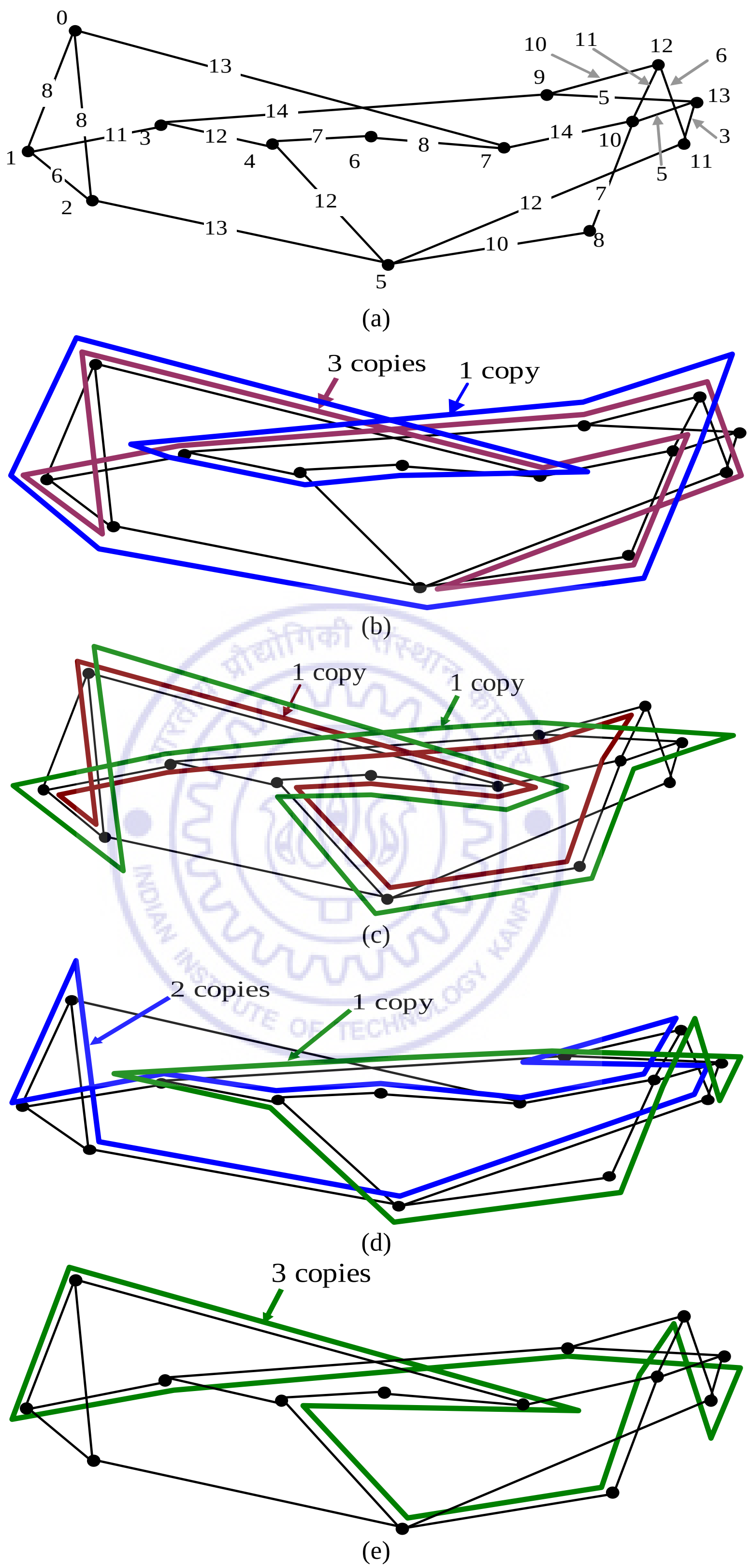

Figure 5-3 Solution set of SCO model for Net2, (a) Working capacities on each span, (b) to (e) the *p*-cycles with number of copies as obtained with the SCO model

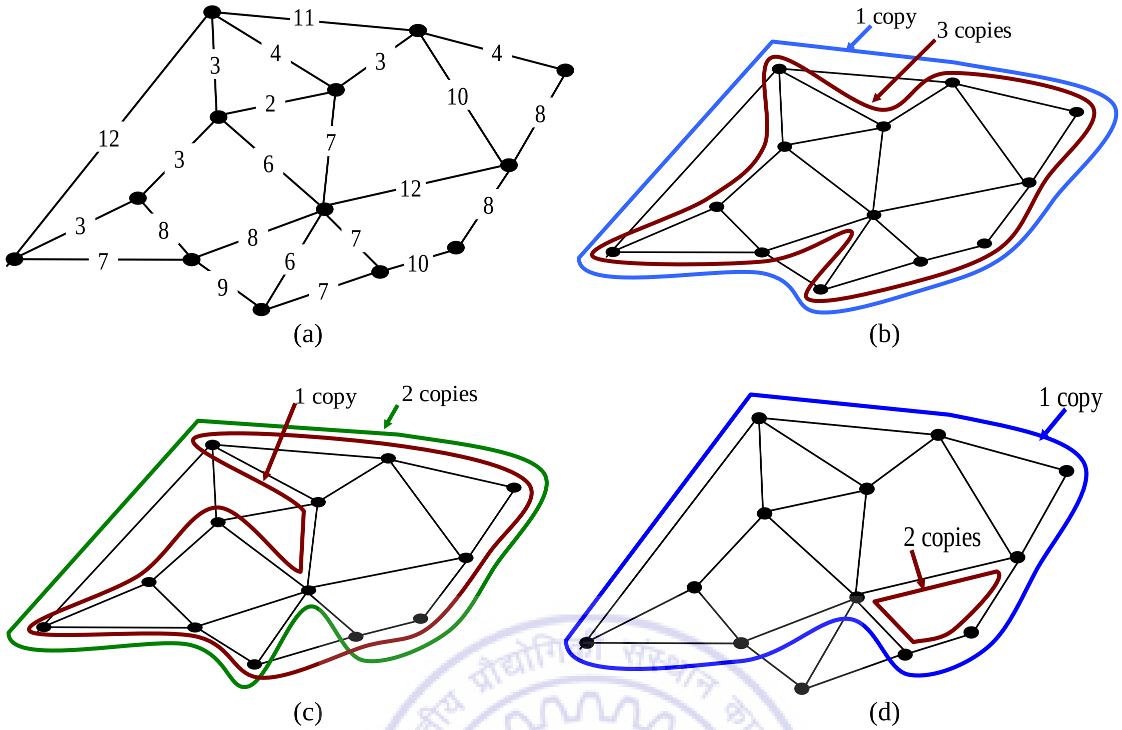

Figure 5-4 Solution set of SCO model for Net3, (a) Working capacities on each span, (b) to (d) the *p*-cycles with number of copies as obtained with the SCO model

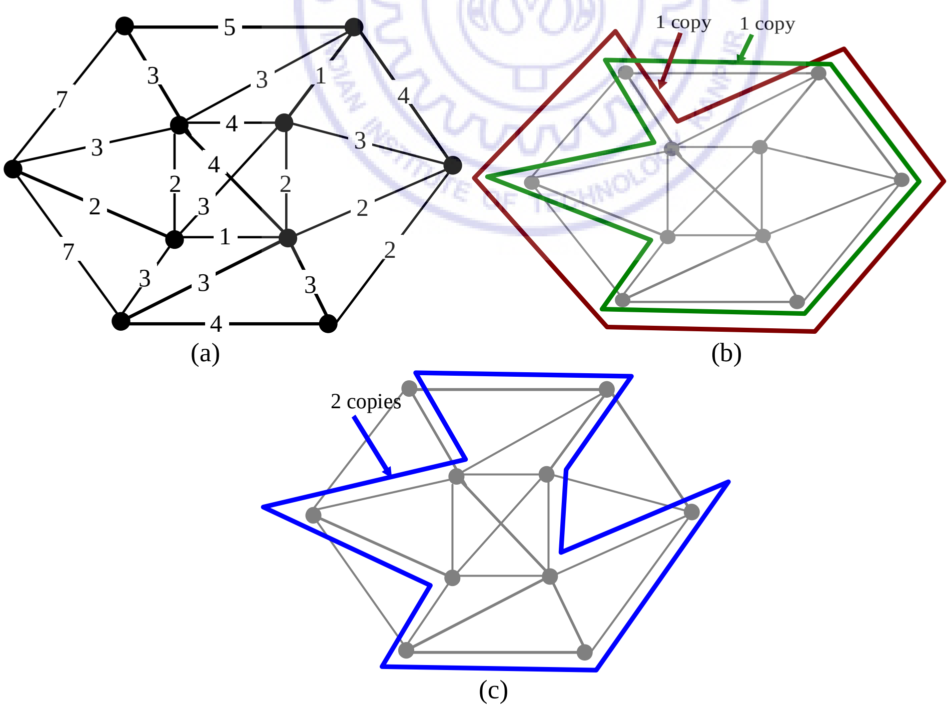

Figure 5-5 Solution set of SCO model for Net4, (a) Working capacities on each span, (b) and (c) the *p*-cycles with number of copies as obtained with the SCO model

In MDCPC, the idea is, to aggregate all the copies of the same *p*-cycle and indicate the number of copies with ‘capacity’ of the *p*-cycle. Then, in case of WDM and DWDM networks, we can have two advantages; one is the computational complexity and signaling traffic will get reduced, and second is waveband switching can be implemented to perform switching at coarser granularity reducing the amount of switching fabrics, . However, to get these advantages, we don’t want to compromise on any of the features of DCPC. We have modified the DCPC protocol such that all the copies of the same *p*-cycle can be found in single iteration without compromising on any of the features of DCPC. To justify MDCPC, the advantages of waveband switching have been given in brief before discussing MDCPC.

5.2.1 ADVANTAGES OF WAVEBAND SWITCHING

As mentioned earlier in section 1.3.2, single fiber can carry up to 160 wavelengths each having a capacity of 10 Gbps. One can imagine the pressure to perform on the optical cross connects (OXCs) in transparent optical networks, because of such high capacities. Consequently, OXCs need to have large number of ports. This will have direct impact on the complexity associated with control, management as well as cost of the OXCs. In recent times, waveband switching has gained tremendous attention due to its ability of reducing number of ports, control complexity and thus, the cost of optical cross connects (OXCs).

In the waveband switching, a subset of wavelengths are grouped together to form a band and the band is switched optically as a single entity using a single port through a transparent optical network infrastructure [137]-[140]. The key advantage of this technique is that fewer ports are required on the switch fabrics of OXCs at intermediate nodes. With MDCPC the advantages of waveband switching can be incorporated in transparent optical networks.

5.2.2 MODIFIED DCPC (MDCPC)

An additional ‘capacity’ field is included in the statelets broadcast by the cycler nodes. This capacity field stores the number of working wavelengths which can be protected by the *p*-cycle among all its on-cycle spans and half of the working wavelengths which can be protected on straddling spans. When statelet reaches to a tandem node the capacity field is also modified. The tandem node compares the following capacity field value in the statelet.

- spare capacity of the span, to which the statelet is to be broadcast
- working capacity of the span, to which the statelet is to be broadcast, and
- half of the working capacity on spans with straddling relationships at the current tandem node.

Then tandem node puts the minimum value in the capacity field.

When the cycler node receives any incoming statelet within sampling duration, then a *p*-cycle is formed. The score and capacity of the *p*-cycle are stored. When another *p*-cycle is formed at the cycler node then its score is compared with the score present *p*-cycle. The *p*-cycle with better score is retained. If both have the same score then the capacity of the two is compared, and better one is retained. In case, both the parameters are same, then the *p*-cycle is chosen randomly.

Then as in DCPC, one by one each node acts as the cycler node and finds the best *p*-cycle based on the above modification. The cycle with the highest score is selected as the *p*-cycle of choice. If there are two or more *p*-cycles with same score then the *p*-cycle with better capacity is selected and if capacity is also same then selection is based on ordinal rank of the nodes involved. *It should be noted that due to the use of capacity field in the p-*

cycle selection, the set of p-cycles formed by MDCPC may not be same as formed by DCPC.

For the deployment, management and maintenance of the *p*-cycles, the cycler node of the selected *p*-cycle is responsible. As all the copies of the same *p*-cycle can now be found in single iteration and aggregated together, the computational complexity and signaling traffic will reduce significantly; and the management of *p*-cycles also becomes much simpler.

Another advantage obtained with this aggregation is that with the help of waveband switching, protection can be provided with coarser granularity in fully convertible optical networks, reducing the control complexity associated with switching of the OXCs. The advantages of the aggregation can be explained as follows. In case of DCPC, to deploy the *p*-cycle, one cross-connection is required at every node of the *p*-cycle between the incoming and outgoing spare wavelength. Thus, the number of cross-connections for all the copies of the same *p*-cycle will be equal to the number of cross-connections of one *p*-cycle multiplied by the number of copies of the *p*-cycle. Obviously, the control complexity associated with switching will be more. With waveband switching, all the copies of the *p*-cycle can be deployed together, with only one waveband cross-connection between incoming wavelengths and outgoing wavelengths. Thus, the number of cross-connections required by all the copies together, will be same as required by a single *p*-cycle[8]. Up to twenty wavelengths per waveband have been reported for switching [139]. It should be mentioned here that as given in [141], waveband switching can be realized without

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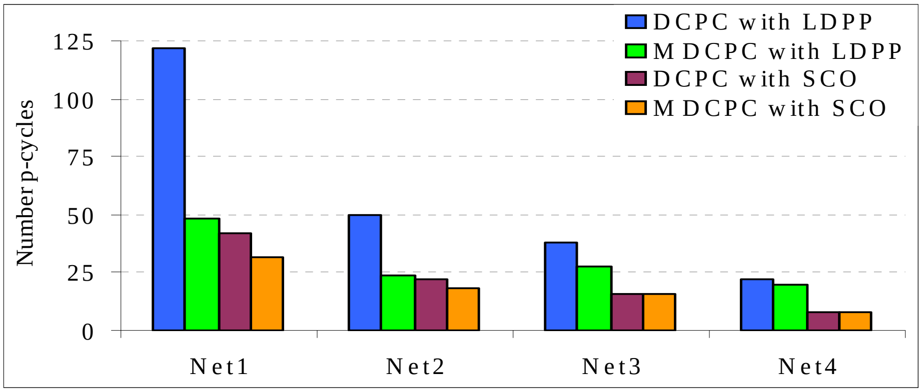
[8] However, a single p-cycle with capacity '*c*' will now provide protection to '*c*' wavelengths on every on-cycle span and '*2c*' wavelengths to every straddling span of the p-cycle.

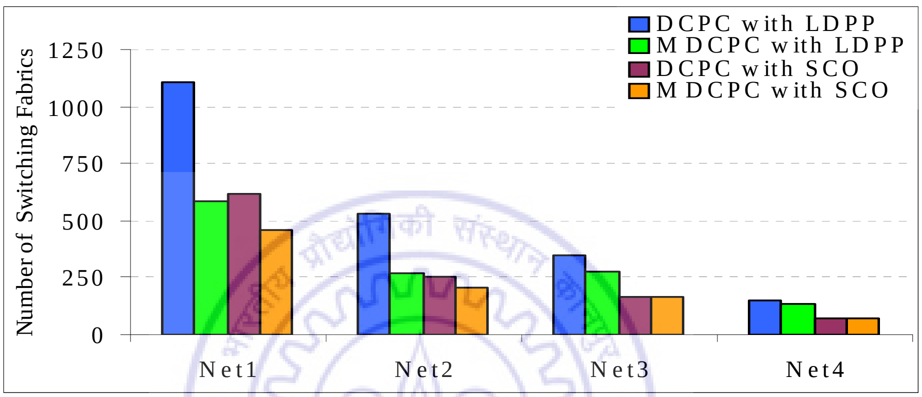
requiring any changes in the hardware of the network, provided the waveband signals fit within the allowable optical pass-bands. Hence, complexity and cost of optical switches are expected to reduce significantly. There is a constraint that the spare capacity in every span which forms *p*-cycles, is on the same set of wavelengths. *In reality, the set of wavelengths which are continuously available between the incoming link as per the statelet and the next hop for the statelet should be used to determine the capacity of p-cycle*. Here, for simplicity, we have assumed that the network is fully convertible. As the number of *p*-cycles reduces, management of the *p*-cycles at a node also simplifies. All this can be done without compromising any advantage of DCPC; only a capacity field is to be added in the statelets.

5.2.3 PERFORMANCE OF MDCPC

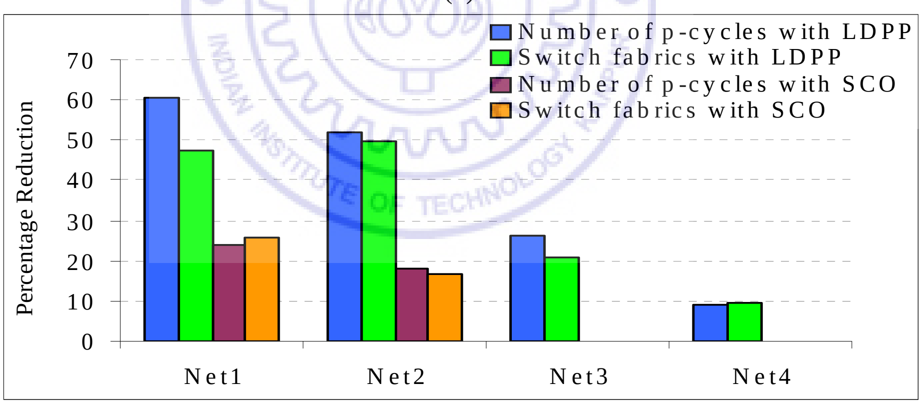
In the first case, the spare capacity provided is equal to the optimum spare capacity obtained by the solution of SCO model and in the second case, the same spare capacity is provided in the spans as required for link disjoint path protection (LDPP). First the *p*-cycles in the network have been found with DCPC as given in [108] (Appendix A). Then the *p*-cycles have been found with MDCPC. With aggregation of *p*-cycles in MDCPC, the total number of *p*-cycles is now much less as compared to total number of *p*-cycles in DCPC (Fig. 5.6(a)). This reduction is more significant when extra capacities are as per LDPP. When extra capacities are as per SCO, then aggregation benefit is less. This is expected as SCO determines least required spare capacity. This will also reduce the computational complexity, as in single iteration DCPC finds only one *p*-cycle, while MDCPC finds all the copies of the *p*-cycle. The reduction in the computational complexity will be the same as the reduction in the number of *p*-cycles as shown in (Fig. 5.6(a)).



(a)



(b)



(c)

Figure 5-6 Effects of MDCPC, (a) Total number of *p*-cycles, (b) Number of switching fabrics, (c) percentage reduction in number of *p*-cycles and switching fabrics

Further with aggregation, there is a significant amount of saving in the total amount of switching fabrics required by the *p*-cycles. We have assumed, that every copy of the *p*-cycle requires one switching fabric at every node in its path in DCPC, while in MDCPC, the aggregated *p*-cycle requires one switching fabric at every node. This switch fabric requirement is shown in Fig. 5.6(b) for all the test networks. The percentage reduction in number of *p*-cycles and amount of switching fabric, is shown in Fig. 5.6(c). It is clear that with larger network, the reduction is more significant. This is due to the fact, that in larger network, the traffic will be more. Hence, more capacity is needed in the network to provide protection. Therefore, number of copies of a *p*-cycle will be more, and with aggregation in MDCPC the reduction in the number will be more.

The maximum reduction in the number of *p*-cycles is for Net1 (Fig. 5.6(a)), as many copies of the same *p*-cycle exist in the network, again due to more spare capacity. For Net3 and Net4, the difference between DCPC and MDCPC with LDPP, is small and there is no difference with SCO (Fig. 5.6(a)). These two networks are relatively smaller network and all the *p*-cycles found with DCPC are single. Hence, there is no effect of aggregation. Therefore in Fig. 5.6(c), the percentage reduction in the number of *p*-cycles and the switching fabric is zero. This is to be mentioned, that with spare capacity provided as in SCO, 100 percent protection with DCPC is not guaranteed (100 percent protection has been achieved only for Net4).

5.3 CONCLUDING COMMENTS

In this chapter, with comparative study between score vs. numpath, we have found that any metric could be used with slight advantage over other in different average nodal degree networks. The performance differences between two metrics are not significant.

In real networks which are having large number of nodes and large amount of traffic, MDCPC provides significant advantage. It helps in reducing the computational complexity, and number of switching fabrics significantly, by adding only a ‘capacity’ field in the statelets used for the formation of *p*-cycles in DCPC. The MDCPC can be implemented even in operational networks employing DCPC, to get the advantage of waveband switching.

CHAPTER 6
REMOVAL OF LOOP BACKS[9]

A lot has been discussed in the literature about the formation of the *p*-cycles; however, there are various issues still to be addressed. One such issue is the length of the restored path. In the current chapter, this issue is discussed in detail. An algorithm with its mathematical model has been proposed for second phase reconfiguration of the restored path to remove loop backs. A formula, for the restored path lengths for the networks having average nodal degree equal to two, has also been derived. The effect of the algorithm on the restored path lengths in various scenarios has been investigated.

6.1 INTRODUCTION

The key advantages of *p*-cycles are 'mesh like efficiency' and 'ring like speed'. As mentioned earlier, the mesh like efficiency of the *p*-cycles is due to the shared protection provided by them to all the on-cycle as well as straddling spans. The ring like speed is due to the pre-configuration of the *p*-cycle and in the event of any span failure the switching is required only at the nodes adjacent to the failed span. While providing *p*-cycle based protection in any network, one has to make sure that the above two features should remain intact. The centralized methods of *p*-cycle formation (Section 4.2.1) help us in finding the optimum capacity for *p*-cycle based protection for static traffic scenarios. Theoretically,

[9] This chapter is based on the previously published work [142] - [144].

one can find the minimum amount of capacities required for a given static traffic matrix. The SCO method is the most popular of all the centralized methods. This ILP model can provide solution within reasonable amount of time and minimizes the spare capacity.

The *p*-cycles in the solution set obtained with SCO model are shown in Fig. 5.2 to Fig. 5.5, for uniform traffic of unity from each node to every other node. It has been observed that most of the formed *p*-cycles are large and only few of them are small for all the test networks. The above results include mostly Hamiltonian or near Hamiltonian (just one node less than the total number of nodes in the network) *p*-cycles in the solution set. Let us find the length of the restored path with these *p*-cycles. The increase in the length of the path is going to be equal to the length of the *p*-cycle minus two as failed link has already reduced the path length by one. In the worst case, with Hamiltonian *p*-cycles, it will be equal to the number of nodes in the network minus two. Let us consider Fig. 6.1, the working path is 3, 4, 5 – two hops long, the Hamiltonian *p*-cycle 0, 8, 7, 6, 5, 4, 3, 2, 1, 9, 12, 10, 11, 0 – thirteen hops long provides restoration path 3, 2, 1, 9, 12, 10, 11, 0, 8, 7, 6, 5, 4, 5 - thirteen hops long in case of failure of span 3-4. The additional path length added due to restoration by *p*-cycle is eleven i.e. thirteen minus two.

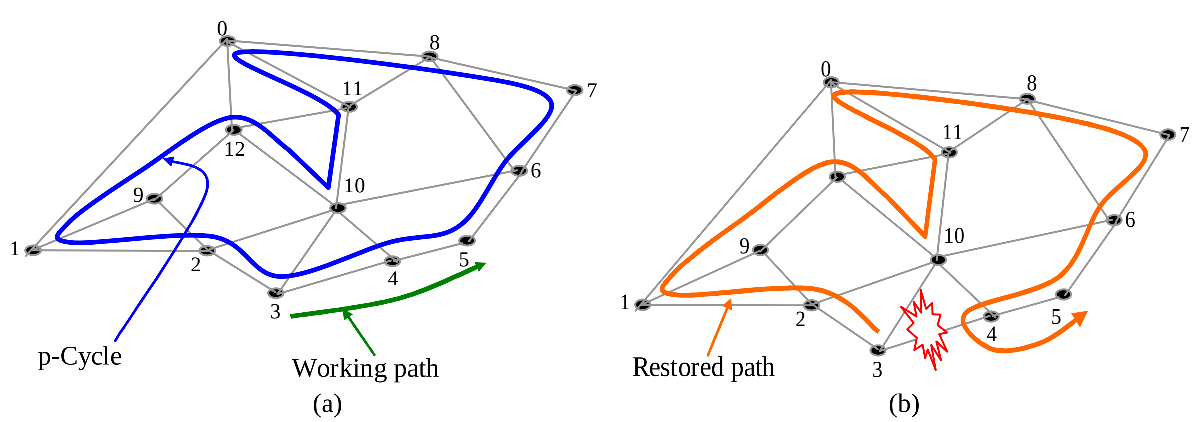


Figure 6-1 Increase in the restored path length, (a) Working path –two hops long and the Hamiltonian *p*-cycle –thirteen hops long, (b) restored path – thirteen hops long

The larger lengths of the *p*-cycles are desirable till the occurrence of failure, as they provide protection to all the on cycle and the straddling spans on shared basis. However, as soon as there is failure of any span, then the *p*-cycles of the solution set will provide restoration to all the paths passing through the failed span. After that, protection can not be provided to the other on-cycle and straddling spans, as the *p*-cycles have been consumed to restore the traffic of the failed span. At the same time, the total restored path lengths will also be quite large. Due to the large restored path lengths, the following problems may arise, mainly in case of long haul networks.

- Excessive signal degradation.
- Excessive signal delay.
- More resources are consumed for restoration in the event of failure.
- Due to larger number of hops, the reliability of the restored path will be less.
- Usually after the restoration of traffic in the event of failure, reconfiguration of the network takes place to survive the second failure. Fewer resources are available for reconfiguration to be done by distributed protocols for second failure protection.

In the networks under consideration, the failure rate is one fiber cut in four days [37] and single fiber can carry more than 160 wavelengths using dense wavelength division multiplexing (DWDM) technique [14]. Therefore, above problems cannot be ignored in case of optical networks. The problems can be minimized if the length of the restored path could be shortened.

We have developed a mathematical model and an algorithm for second phase reconfiguration of the restored path, to reduce its length while retaining all the advantages of *p*-cycles. It is obvious that with large length of the *p*-cycles many nodes are going to be repeated in the working path and the restoration path provided by the *p*-cycle in the event of failure. Hence, there will be loop backs in most of the cases, due to these repetitions. In the next section, the concept of loop backs is explained.

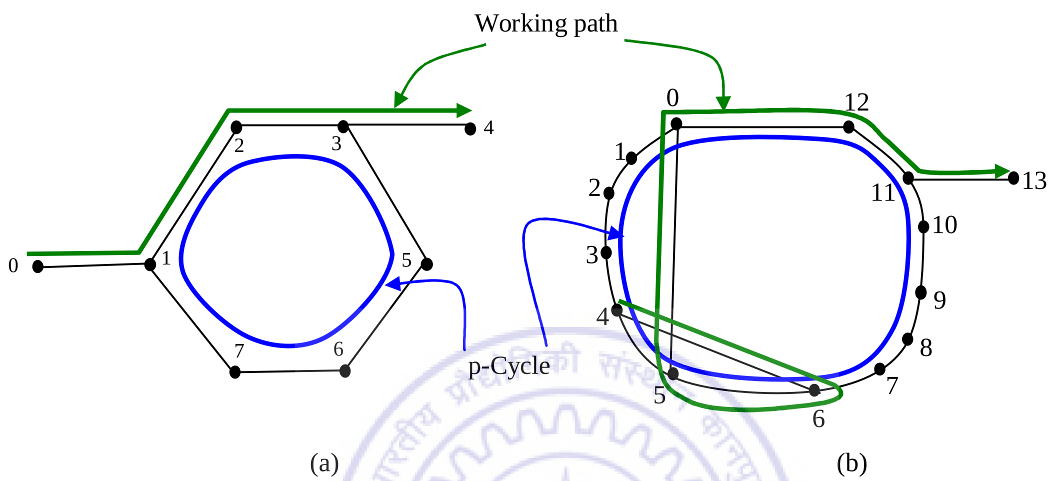


Figure 6-2 Working path and *p*-cycle in Net A and Net B

6.2 CONCEPT

Consider the networks shown in Fig. 6.2. We are assuming that the networks are fully convertible (we are showing the network connections in one direction and assuming that corresponding symmetrical network will exist for reverse direction also, Fig. 4.6). Let us consider the working path 0, 1, 2, 3, 4 (shown by dotted line) from source '0' to destination '4', in Net A. The *p*-cycle s 2, 1, 7, 6, 5, 3, 2 formed in the spare capacity, is protecting the spans 2, 3 in Net A along with other spans (Fig. 6.2(a)). Let us consider the failure of on-cycle span 2, 3 in Net A (Fig. 6.2(a)). The working path 0, 1, 2, 3, 4 (shown by dotted line) which is passing through the failed span, will now be routed via the other portion of the *p*-cycle, i.e. 2, 1, 7, 6, 5, 3. The restored path will now be 0, 1, 2 – 2, 1, 7, 6, 5, 3 – 3, 4 (shown by dashed line in Fig. 6.3(a)), where 0, 1, 2 and 3, 4 are the portions of the working path and 2, 1, 7, 6, 5, 3 is the path provided by the *p*-cycle. If any node is common between the working path and the *p*-cycle, except the end nodes of the failed span, then the restored path will pass through that node twice. This is called loop back in the present work. In the restored path, node 1 is visited twice; hence there is a loop back at node 1. In this example, the loop back is only at a single node.

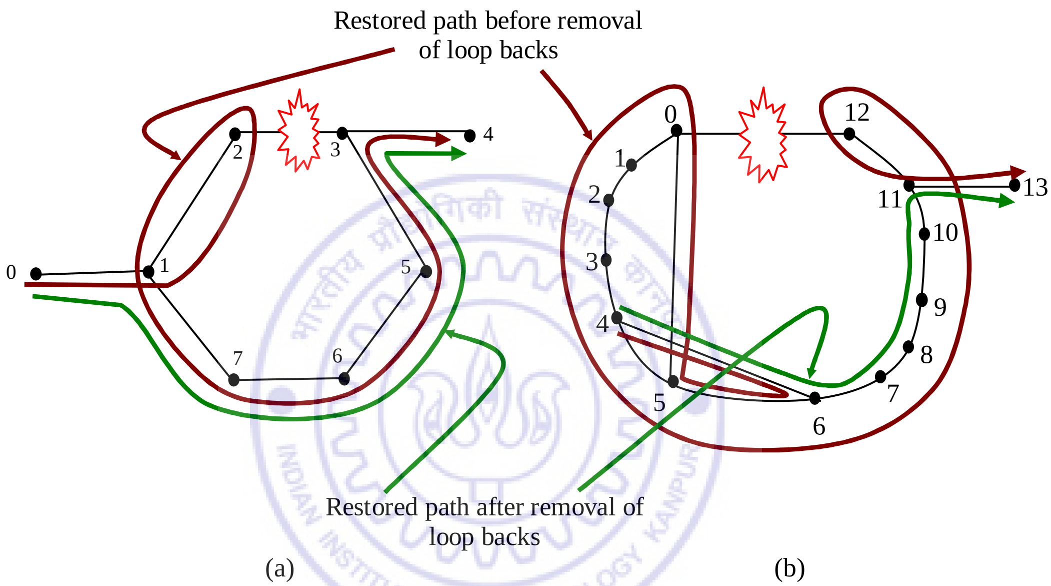


Figure 6-3 Removal of loop backs

If the number of common nodes in the working path and the restoration path provided by the *p*-cycle are more, then there will be more loop backs. Refer to Fig. 6.2(b), the working path is 4, 6, 5, 0, 12, 11, 13 from source ‘4’ to destination ‘13’ and the *p*-cycle 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 0 formed in the spare capacity, is protecting the span 0, 12 along with other spans in Net B. Let us consider the failure of span 0, 12. In the event of failure, the restoration path provided by the *p*-cycle, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, will restore the working path 4, 6, 5, 0, 12, 11, 13, and the restored path will be 4, 6, 5, 0 – 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 – 12, 11, 13, and common nodes will be 4, 5, 6, and 11

(Fig. 6.3(b)). Here, 0 and 12 are the end nodes of the failed link, hence, they are not considered as common nodes. There will be loop backs at the nodes 4, 5, 6, and 11, and the paths of the loop back will be at node 4 – 4, 6, 5, 0, 1, 2, 3, 4, at node 5 – 5, 0, 1, 2, 3, 4, 5, and at node 6 – 6, 5, 0, 1, 2, 3, 4, 5, 6 and at node 11 – 11, 12, 11. If the loop backs can be removed from the restored path, then the restored path length will be reduced significantly as well as redundant capacity will also be released. After removal of loop backs, the final paths are 0, 1, 7, 6, 5, 3, 4 and 4, 6, 7, 8, 9, 10, 11, 13 in Net A and Net B respectively (Fig. 6.3 (a) and Fig. 6.3 (b)).

To remove these loop backs from the restored path without compromising the key features of the *p*-cycles, an algorithm removal of loop back (RLB) is presented. The RLB algorithm will not interfere with the routing of working paths and the formation of *p*-cycles. Hence, 'mesh like efficiency' will not be effected. After the occurrence of a failure, to retain the 'ring like speed' of the *p*-cycle, the working paths are restored by the *p*-cycles in the traditional way [108] i.e. restoration of the path is done in the first phase. In the second phase the loop backs are removed by reconfiguration of the restored path using RLB. In this way the RLB reduces the restored path length and also releases the redundant capacity which is otherwise engaged unnecessarily.

The loop backs can also be removed with the concept of path segment with flow *p*-cycles [66]. The flow *p*-cycles are used to protect the path-segment crossing the *p*-cycle. The removal of loop backs can also be viewed as the protection of complete path segment (common with the flow *p*-cycle), instead of only the failed link. However, the speed of the *p*-cycle is compromised in this scenario as well as more complexity is involved in finding the flow *p*-cycles which protects the path segments [66]. The flow *p*-cycle based restoration has the speed of 1:1 path protection [66]. Further, method of finding flow *p*-cycles falls under the centralized category. Whereas, with our scheme, path segment protection can be implemented as a result of removal of loop back in distributed fashion, and our concept works independently of the method used to form the *p*-cycles. At the same time, the fast restoration feature of the *p*-cycles is also retained. However, the initial capacity requirement of flow *p*-cycle is less than that of the SCO model of selecting optimum *p*-cycles.

To release the loop back capacity, the loop with the longest path length should be removed, to reconfigure the restored path. It is obvious that removal of the longest loop, will release the maximum number of links. The loop with the longest path length is identified both at the source and the destination ends, and then the switching action is performed at the corresponding common nodes. This reconfigures the restored path. All the other nodes which are part of the loop back paths, modify the state information about the capacity involved with loop backs, as released. In Fig. 6.3(a), the switching action will be performed at 1, and states at 2 and 1 for the capacities used by the loop back path between 1, 2, 1, are set as unused to release the loop back. Now, the final path will be 0, 1, 7, 6, 5, 3, 4. In Fig. 6.3(b), the switching action will be performed at 6 at the source end, and at 11 at the destination end, to have the final path as 4, 6, 7, 8, 9, 10, 11, 13. At nodes 6, 0, 1, 2, 3, 4, 5 and 11, 12 nodes, the status for capacity involved in loop back, is set as released. The mathematical model and the flow chart for the same are given in thenext section.

6.3 MATHEMATICAL MODEL

The flow chart for the RLB algorithm is given in Fig. 6.4. The full mathematical model is presented below. The variables used in the model are defined as follows.

W_i Set of working paths passing through failed span *i* indexed by *r*.

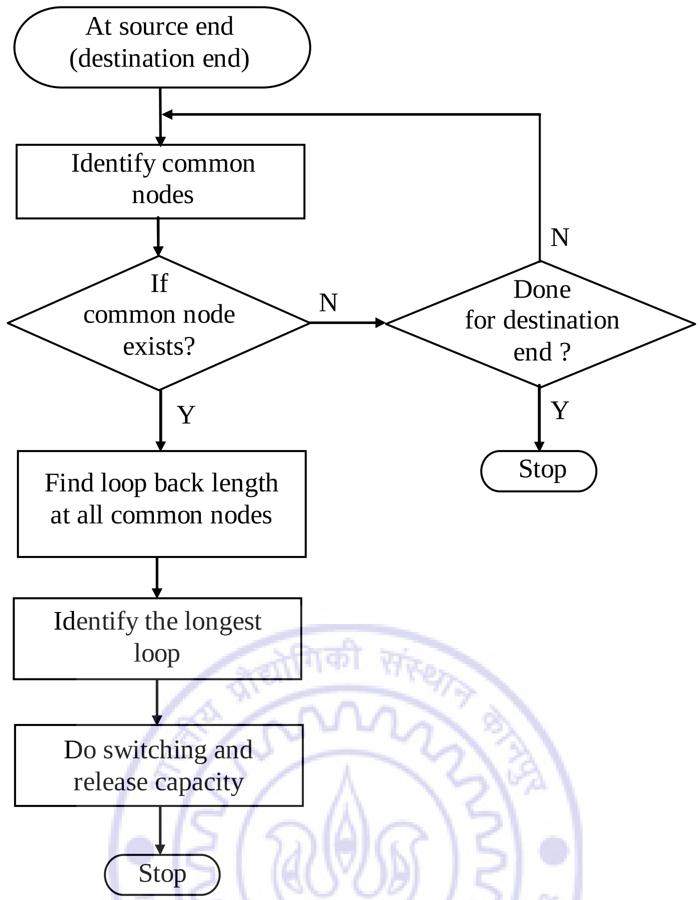


Figure 6-4 Flow chart for RLB

S Set of spans, indexed by *i* (failed) or *j* (surviving).

P Set of *p*-cycles indexed by *p*.

[ ] Ordered set of nodes

[R] Nodes of the working path from source to destination.

[F] The failed span (F_1, the upstream node, and F_2, the downstream node).

[C] The *p*-cycle with the nodes organized in such a way that F_1 is the first node and F_2 is the last node in [C].

[O] The portion of the working path from source node to the upstream node of the failed link.

[D] The portion of the working path from downstream node of the failed link to the destination node.

[FP] Restored path before RLB

[FR] Restored path after RLB

L_U The length of [U]; defined as the total number of nodes in the set, minus one.

L(X) The length of the loop back at node X.

J_{UX} index of node X in the set [U]. The index starts from 0 and ends at L_U.

With the help of addition and subtraction operation for ordered sets as defined in section 2.2.1 and section 2.2.2

[R] = [O] + [F] + [D].

In the event of failure of [F], in the first phase [R] is restored in the traditional manner as

[FP] = [O] + [C] + [D].

Then in the second phase, the RLB will work as follows.

First Step: To identify the common nodes in [O] and [C]. Let [N1] be the set of the common nodes of [O] and [C], excluding the F_1, the upstream node of the failed link (at source end).

$N1 = ([O] \cap [C]) - ([O] \cap [C] \cap [F]);$

the second term excludes the end node of the failed link. Note that $[O] \cap [C]$ is not an ordered set hence, normal subtraction operation is used here.

Second Step: To find the longest length of the loop back paths. Length of the loop back path for common node N,

$L(N) = L_O - J_{ON} + J_{CN}$.

Among all elements of N1, take the element X1, having longest loop back length, L(X1).

Now [R1] = [O] – [O1], where [O1] = set of nodes from node at index J_{OX1} to F_1 in [O], in order. If N1 is empty set, then [R1] = [O].

At destination end of the failed link;

First Step: Find N2 = ([D] ∩ [C]) – ([D] ∩ [C] ∩ [F]);

Second Step: The length of loop back path for common node N,

$L(N) = L_C – J_{CN} + J_{DN}$.

Among all elements of N2, take the element, X2, having longest loop back length, L(X2). Now, [R2] = [D] – [D1], where [D1] is the set of nodes from F_2 to node at index J_{DX2} in [D], in order. If N2 is empty set, then [R2] = [D].

Third Step: To remove the loop back path. The final path with loop backs removed, is [FR] = [R1] + (([C] – [C1]) – [C2]) + [R2], where [C1] = set of nodes from F_1 to the node at index J_{CX1} in [C] and [C2] is the set of nodes from node at index J_{CX2} to F_2 in [C]. When set N1 is an empty set, then [C1] will also be an empty set. Similarly, for an empty set N2, [C2] will also be an empty set.

Thus the length of restored path before RLB, will be $L_{FP} = L_O + L_C + L_D$, and after RLB, $L_{FR} = L_O – L_{O1} + L_C – L_{C1} – L_{C2} + L_D – L_{D1}$.

The average length of the restored paths without RLB is defined as

$$L_{WRLB} = \frac{\sum_{\forall i \in S, \forall r \in W_i} (L_{FP})_{r,i}}{\sum_{\forall i \in S, \forall r \in W_i} 1} = \frac{\sum_{\forall i \in S, \forall r \in W_i} (L_{FP})_{r,i}}{\sum_{\forall i \in S} |W_i|} , \qquad (6.1)$$

and with RLB, it is defined as

$$L_{RLB} = \frac{\sum_{\forall i\in S, \forall r\in W_i} (L_{FR})_{r,i}}{\sum_{\forall i\in S, \forall r\in W_i} 1} = \frac{\sum_{\forall i\in S, \forall r\in W_i} (L_{FR})_{r,i}}{\sum_{\forall i\in S,} |W_i|} \quad (6.2)$$

Here $|W_i|$ is the cardinality of set W_i.

The above representation is illustrated using the network shown in Fig. 6.2(a), as follows.

[R] = [0, 1, 2, 3, 4];

[C] = [2, 1, 7, 6, 5, 3]; $L_C = 5$;

[F] = [2, 3]; $F_1 = 2$; $F_2 = 3$;

[O] = [0, 1, 2]; $L_O = 2$; and

[D] = [3, 4]; $L_D = 1$;

Hence [R] = [O] + [F] + [D] = [0, 1, 2] + [2, 3] + [3, 4] = [0, 1, 2, 3, 4],

[O] ∩ [C] = [0, 1, 2] ∩ [2, 1, 7, 6, 5, 3] = [1, 2],

[O] ∩ [C] ∩ [F] = [1, 2] ∩ [2, 3] = [2]; and

N1 = ([O] ∩ [C]) – ([O] ∩ [C] ∩ [F]) = [1, 2] – [2] = [1].

Thus, L(1) = 2.

Then [O1] = set of nodes from node at index J_{O1} to F_1 in [O], hence,

[O1]= [1, 2]; $L_{O1} = 1$;

[R1] = [O] – [O1] = [0, 1, 2] – [1, 2] = [0, 1].

At destination end,

N2 = ([D] ∩ [C]) – ([D] ∩ [C] ∩ [F])

= ([3, 4] ∩ [2, 1, 7, 6, 5, 3]) – ([3, 4] ∩ [2, 1, 7, 6, 5, 3] ∩ [2, 3]) = ([3] – [3])

= [ ],

$L(X2) = 0$, and

$[R2] = [D] = [3, 4]$ and $[D1] = [\ ]$; $L_{D1} = 0$;

$[C1] = [2, 1]$; $L_{C1} = 1$;

$[C2] = [\ ]$; $L_{C2} = 0$;

$[FR] = [R1] + (([C] - [C1]) - [C2]) + [R2]$

$= [0, 1] + (([2, 1, 7, 6, 5, 3] - [2, 1]) - [\ ]) + [3, 4] = [0, 1] + [1, 7, 6, 5, 3] + [3, 4]$.

Thus $[FR] = [0, 1, 7, 6, 5, 3, 4]$ and

$L_{FR} = L_O - L_{O1} + L_C - L_{C1} - L_{C2} + L_D - L_{D1} = 2 - 1 + 5 - 1 - 0 + 1 - 0$

$= 6$.

$[FP] = [O] + [C] + [D] = [0, 1, 2] + [2, 1, 7, 6, 5, 3] + [3, 4] = [0, 1, 2, 1, 7, 6, 5, 3, 4]$ and

$L_{FP} = L_O + L_C + L_D$

$= 8$.

Thus, the final path after reconfiguration will be six hops long (Fig. 6.3(a)), instead of eight hops without reconfiguration. We can observe that with reconfiguration, the restored path length has been reduced by two units.

6.4 MATHEMATICAL BOUND

Further, we have found that the restored path lengths with and without RLB also depends upon the average node degree ($\overline{d}$) [144]. For any network, the minimum $\overline{d}$ can be two for all the nodes to be dual connected. The maximum $\overline{d}$ can be (n-1), where n is the total number of nodes in the network. For $\overline{d}$ equal to two, the network topology will become ring. In this case, the average restored path lengths without RLB and with RLB will be given by (assuming that for every node pair there is a path),

$$L_{WRLB} = \frac{2(n-1)(2n-1)}{3n} \qquad n \text{ is even, and}$$

$$= \frac{2(2n-3)}{3} \qquad n \text{ is odd,} \tag{6.3}$$

and

$$L_{RLB} = \frac{2(n^2-1)}{3n} \qquad n \text{ is even, and}$$

$$= \frac{2n}{3} \qquad n \text{ is odd;} \tag{6.4}$$

respectively.

The derivation is given in Appendix B. For the case of $\overline{d} = n-1$, all the nodes are connected to each other. Hence, length of the working paths will be one hop count. Therefore, when paths are restored with *p*-cycles, there will not be any loop backs. Hence, L_{FP} and L_{FR} will be same and depend upon the length of the *p*-cycles protecting the paths. With Hamiltonian *p*-cycles, these lengths will be $n-1$ for on cycle link failure and $n/2$ on an average for straddling link failures.

6.5 PERFORMANCE EVALUATION OF RLB

We have tested the proposed algorithm with various methods of formation of *p*-cycles for different test networks. Next, the effect of $\overline{d}$ on the restored path length has been found with RLB. The RLB has also been studied by varying n and various traffic distributions. The different models used for the study of RLB are given below.

6.5.1 MODELS USED FOR PERFORMANCE EVALUATION

The proposed RLB algorithm has been tested with various methods of *p*-cycle formation. The most capacity efficient model is SCO (section 4.2.1) model based on ILP. For all theoretical purposes this model is most commonly used. Therefore, the above model has been included for evaluation of RLB. However, this is a centralized method and for real networks, DCPC method of *p*-cycle formation can be used; hence, the second model, we have used is DCPC[10]. Among other methods of *p*-cycle formation, the hop count limited model [86] has also been selected, as this method also deals with the restored path lengths. In this model, the restored path lengths have not been allowed to go beyond the hop count limit.

The hop count limited (H-L) model given in [86] is joint optimization and is used to optimize both the working path lengths and the capacity required for the formation of *p*-cycles with the hop count limit constraint. In the current work, we want to judge the performance of RLB, hence, instead of joint optimization, spare capacity required by the *p*-cycles have been optimized. The modified version of the model of [86], is given below.

Parameters used by us are as follows

Δ A large positive constant (in our case it was 10000, however, any value which is much larger in comparison with maximum working capacity on any span is good enough).

[10] The RLB can be used with MDCPC only when a group of similar working paths are protected by aggregated p-cycle. Presently we are assuming one working path between each source destination pair, hence, the advantage of MDCPC cannot be taken.

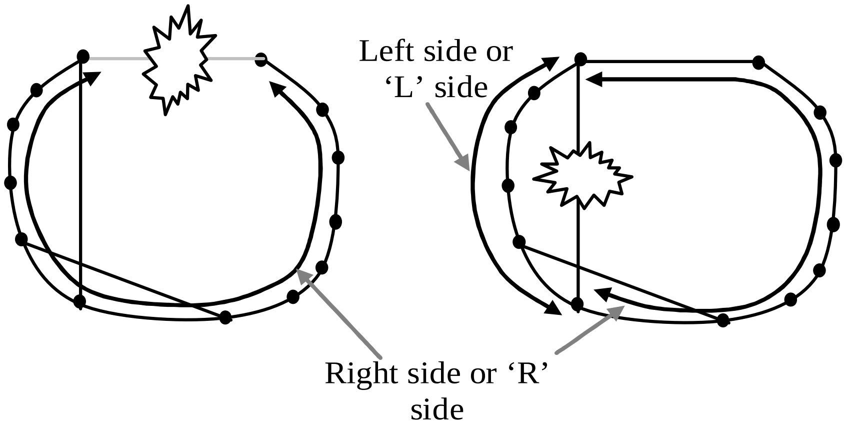


Figure 6-5 Left and right path definitions for (a) on-cycle spans and (b) straddling spans of a *p*-cycle

$x_i^{p,L}$ Equal to 1 if the L side of *p*-cycle p offers an acceptable protection path (protection path less than the hop count limit) for failure of span i, 0 otherwise (L side or left path and R side or right path nomenclature as used in [86] are shown in Fig. 6.5).

$x_i^{p,R}$ Equal to 1 if the R side of *p*-cycle p offers an acceptable protection path for failure of span i, 0 otherwise.

π_j^p Equal to 1 if *p*-cycle p crosses span j, 0 otherwise

w_j Working capacity on span j.

Variables used are as follows

T_{sp} Total spare capacity required for the formation of *p*-cycles

sp_j Spare capacity required on span j.

n^p Number of unit-capacity copies of *p*-cycle p in the solution.

n_i^p Number of copies of *p*-cycle p used to protect span i.

$n_i^{p,L}$ Number of copies of *p*-cycle p required for protection of span i, when the L side of the cycle is used.

$n_i^{p,R}$ Number of copies of *p*-cycle p required for protection of span i, when the R side of the cycle is used.

The objective is to minimize

$$T_{sp} = \sum_{\forall j \in S} sp_j \quad , \tag{6.5}$$

subject to

$$\sum_{\forall p \in P} (x_i^{p,L}.n_i^{p,L} + x_i^{p,R}.n_i^{p,R}) \geq w_i \qquad \forall i \in S \ , \tag{6.6}$$

$$\sum_{\forall p \in P} \pi_i^p.n^p = sp_i \qquad \forall i \in S, \tag{6.7}$$

$$n_i^p \geq n_i^{p,L} \qquad \forall i \in S, \qquad \forall p \in P \ , \tag{6.8}$$

$$n_i^p \geq n_i^{p,R} \qquad \forall i \in S, \qquad \forall p \in P, \tag{6.9}$$

$$n^p \geq n_i^p \qquad \forall i \in S, \qquad \forall p \in P, \tag{6.10}$$

$$n_i^{p,L} \leq \Delta.x_i^{p,L} \qquad \forall i \in S, \qquad \forall p \in P, \tag{6.11}$$

and

$$n_i^{p,R} \leq \Delta.x_i^{p,R} \qquad \forall i \in S, \qquad \forall p \in P. \tag{6.12}$$

The objective function in Equation (6.5), minimizes the total spare capacity required to form the *p*-cycles. The L and R paths of the *p*-cycle p, for straddling span protection, have been considered separately. Equation (6.6) ensures that all the working capacity will be protected either by L or R paths of the *p*-cycles. Equation (6.7) ensures enough spare capacity on every span to form all the *p*-cycles. Equations (6.8) to (6.10) make sure that copies of *p*-cycle p should be equal to or greater than the number of copies required by any single span failure. Equations (6.11) and (6.12) are 'backup' constraints to ensure that, if *p*-cycle p is not eligible to restore span i using either the L or R side, then it will not be considered for protection of that span.

In the above model, we have eliminated the parameters, variables and constraints which are related with routing of working paths in [86]. We have used shortest path Dijkstra's algorithm with hop count as metric for routing of working paths. Obviously, $\sum_{\forall j \in S} w_j$ will be minimum, however, there will be some effect on the total spare capacity required to form the *p*-cycles. Since, there is hop count constraint for restored path lengths, the length of the path provided by the *p*-cycle for protection will not be affected, and we can safely compare the results of RLB with H-L model with results from other models.

6.5.2 Performance with SCO, DCPC, and H-L Model

It is obvious that the RLB algorithm will almost always reduce the restored path lengths. In order to verify this hypothesis, the algorithm has been tested as follows.

To generate the working capacity on each span, the working traffic assuming unit traffic matrix, is routed with shortest path Dijkstra's algorithm using hop count as the metric for all the evaluations. All the cycles of the network graph have been found in advance. A simulator, developed by us in Java has been used for this purpose. The ILP models have been solved with CPLEX 9.0 using data files generated with Java based simulator. The *p*-cycles have been formed as given below.

- ***WITH SCO MODEL***

The solution set of optimal *p*-cycles to protect all the working capacities on each span has been found with SCO model given in (section 4.2.1).

- ***WITH DCPC***

The DCPC model finds the *p*-cycles in the spare capacity available on the spans. The spare capacity in each span is assumed to be the same as obtained in the SCO model, and then the *p*-cycles are formed with DCPC. The DCPC protocol has been simulated in our simulator.

- ***WITH H-L MODEL***

The H-L model from section 6.5.1 has been used to find the solution set of optimum *p*-cycles. Since we are comparing the performance of RLB in H-L case with SCO and DCPC, thus, the hop count limit is kept equal to the number of nodes in the network, to have similar operating conditions. As given in [86], with higher hop count limit the spare capacity required by H-L model will be same as SCO model. Whereas for lower hop count limit, the spare capacity required are quite higher. The performance variations with hop count limit have been discussed later.

- ***TEST METHOD***

After finding the solution set of *p*-cycles, to evaluate the performance for single failure, the L_{WRLB} and L_{RLB} (Equations 6.1 and 6.2) values have been calculated by considering the failure of every span one at a time. For finding L_{WRLB} and L_{RLB}, all the paths passing through the failed span (links[11]) are identified. The *p*-cycles, which are protecting the failed span, are also identified. The failed span may be on-cycle on some *p*-cycles or straddling span on some other *p*-cycles. To protect all the working capacity of every span, sufficient numbers of *p*-cycles are required. With SCO and H-L model, all the working capacity of the network is protected. However with DCPC, hundred percent protection is not guaranteed with minimum spare capacity provided as per SCO [108]. If all the working capacity of the network could not be protected with the formed *p*-cycles then sufficient number of copies are added to the *p*-cycle which can protect maximum number of unprotected working capacity. This is repeated till all the working capacities are protected. The resulting *p*-cycle set for DCPC has been used by us for performance evaluation.

To protect a link of the span, any one of the L or R paths of the *p*-cycle can be used. We have taken each link one by one from the set of all the links of the span and a *p*-cycle also one by one from the solution set of *p*-cycles to protect the link. In this way L_{WRLB} is calculated, after that RLB has been used to remove the loop back and then L_{RLB} is calculated. The total number of paths and the length of the restored paths before and after RLB for every span have also been found separately. The results for all the test networks (Fig. 5.1) are shown in Tables 6.1 to 6.12 and Fig. 6.7 to Fig. 6.10. In the results, the spans having maximum reduction in the restored path length are highlighted with blue colour, with maximum reduction in terms of percentage are highlighted with green colour, and with zero reduction are highlighted with grey colour. If maximum reduction and maximum percent reduction are same, again green colour has been used.

[11] One link is equivalent to one working capacity of the span.

Table 6-1 Results of RLB for Net1 with SCO Model

Net1 (Total spare capacity T_{sp} = 754)							
RLB with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	828	388	440	53.14
2	0, 3	18	52	160	144	16	10.00
3	0, 9	68	262	912	582	330	36.18
4	1, 2	22	76	338	254	84	24.85
5	2, 3	16	52	140	96	44	31.43
6	2, 4	22	64	364	280	84	23.08
7	3, 5	30	104	508	284	224	44.09
8	4, 5	30	104	268	198	70	26.12
9	4, 6	32	106	582	384	198	34.02
10	5, 8	48	172	640	380	260	40.63
11	5, 9	24	78	198	186	12	6.06
12	6, 7	28	90	498	330	168	33.73
13	7, 8	56	194	642	422	220	34.27
14	7, 11	44	158	780	472	308	39.49
15	8, 9	54	194	742	376	366	49.33
16	8, 10	66	246	896	564	332	37.05
17	9, 18	70	248	898	682	216	24.05
18	10, 11	20	54	190	178	12	6.32
19	10, 14	64	236	798	516	282	35.34
20	10, 18	26	72	334	258	76	22.75
21	11, 12	36	128	664	372	292	43.98
22	12, 13	12	30	178	146	32	17.98
23	13, 14	32	116	584	352	232	39.73
24	14, 15	24	74	448	260	188	41.96
25	15, 16	20	66	372	260	112	30.11
26	16, 17	4	6	60	56	4	6.67
27	16, 18	40	144	360	264	96	26.67
28	17, 18	32	108	554	308	246	44.40

Table 6-2 Results of RLB for Net1 with H-L Model

Net1 (Total spare capacity T_{sp} = 754)							
RLB with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	828	422	406	49.03
2	0, 3	18	52	164	96	68	41.46
3	0, 9	68	262	912	570	342	37.50
4	1, 2	22	76	338	222	116	34.32
5	2, 3	16	52	84	84	0	0.00
6	2, 4	22	64	356	284	72	20.22
7	3, 5	30	104	532	292	240	45.11
8	4, 5	30	104	268	204	64	23.88
9	4, 6	32	106	594	396	198	33.33
10	5, 8	48	172	640	404	236	36.88
11	5, 9	24	78	148	148	0	0.00
12	6, 7	28	90	510	338	172	33.73
13	7, 8	56	194	650	432	218	33.54
14	7, 11	44	158	794	474	320	40.30
15	8, 9	54	194	742	384	358	48.25
16	8, 10	66	246	896	566	330	36.83
17	9, 18	70	248	898	632	266	29.62
18	10, 11	20	54	146	96	50	34.25
19	10, 14	64	236	828	620	208	25.12
20	10, 18	26	72	334	268	66	19.76
21	11, 12	36	128	668	362	306	45.81
22	12, 13	12	30	182	154	28	15.38
23	13, 14	32	116	588	360	228	38.78
24	14, 15	24	74	446	260	186	41.70
25	15, 16	20	66	370	258	112	30.27
26	16, 17	4	6	58	54	4	6.90
27	16, 18	40	144	332	250	82	24.70
28	17, 18	32	108	552	306	246	44.57

Table 6-3 Results of RLB for Net1 with DCPC Model

Net1 (Total spare capacity T_{sp} = 922)							
RLB with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	856	512	344	40.19
2	0, 3	18	52	358	172	186	51.96
3	0, 9	68	262	880	578	302	34.32
4	1, 2	22	76	450	302	148	32.89
5	2, 3	16	52	84	84	0	0.00
6	2, 4	22	64	438	346	92	21.00
7	3, 5	30	104	558	338	220	39.43
8	4, 5	30	104	314	244	70	22.29
9	4, 6	32	106	628	440	188	29.94
10	5, 8	48	172	580	364	216	37.24
11	5, 9	24	78	486	272	214	44.03
12	6, 7	28	90	544	392	152	27.94
13	7, 8	56	194	664	436	228	34.34
14	7, 11	44	158	840	514	326	38.81
15	8, 9	54	194	892	418	474	53.14
16	8, 10	66	246	996	488	508	51.00
17	9, 18	70	248	828	540	288	34.78
18	10, 11	20	54	194	110	84	43.30
19	10, 14	64	236	786	530	256	32.57
20	10, 18	26	72	510	198	312	61.18
21	11, 12	36	128	722	410	312	43.21
22	12, 13	12	30	234	198	36	15.38
23	13, 14	32	116	652	380	272	41.72
24	14, 15	24	74	482	248	234	48.55
25	15, 16	20	66	406	270	136	33.50
26	16, 17	4	6	74	70	4	5.41
27	16, 18	40	144	484	332	152	31.40
28	17, 18	32	108	628	324	304	48.41

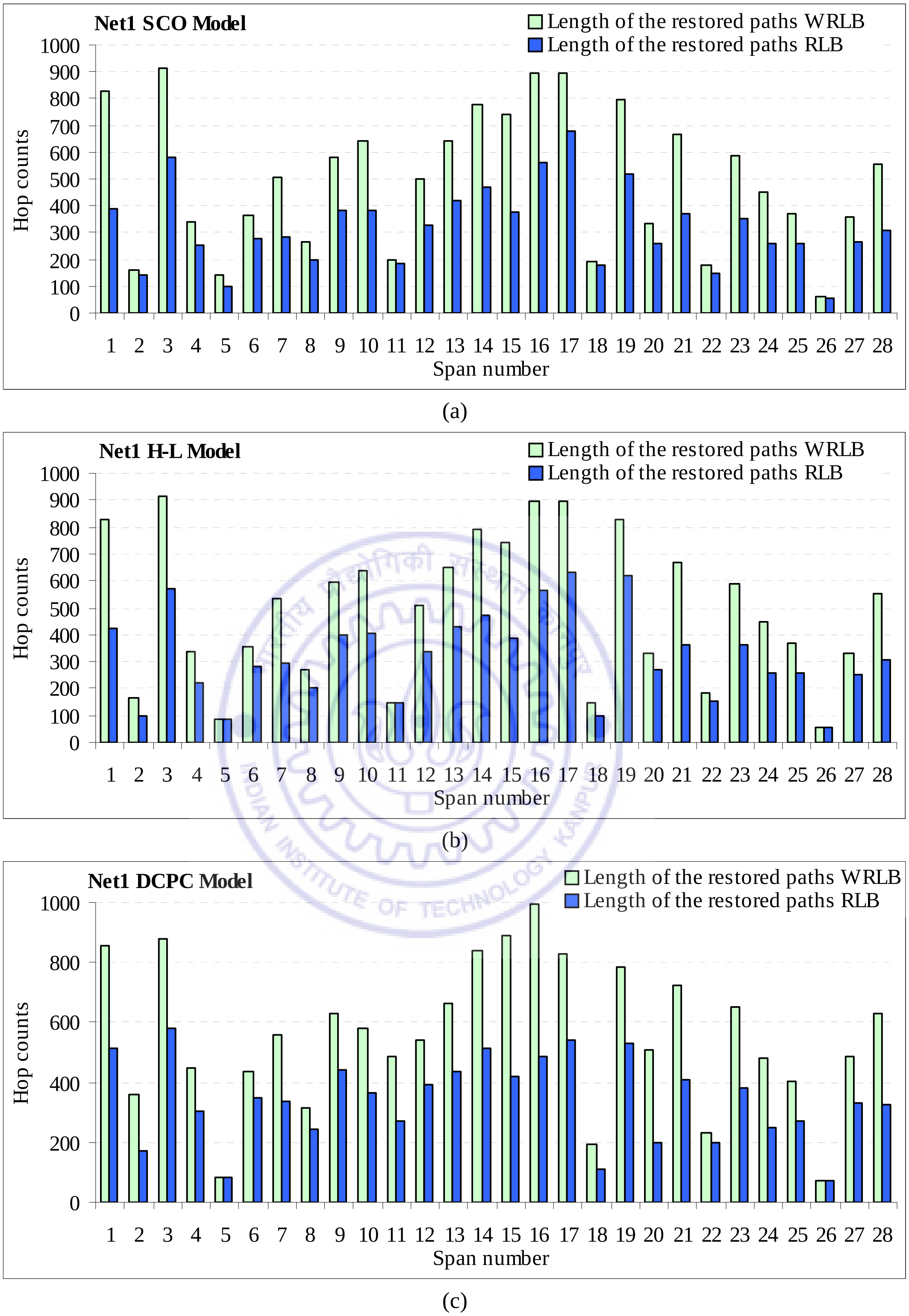


Figure 6-6 Length of the restored paths without RLB and with RLB for Net1

Table 6-4 Results of RLB for Net2 with SCO Model

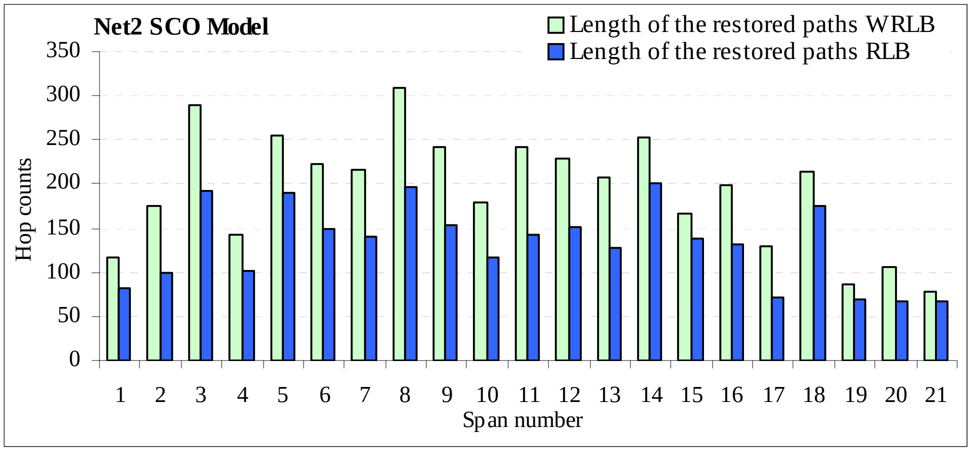
Net2 (Total spare capacity T_{sp} = 286)							
RLB with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	116	82	34	29.31
2	0, 2	16	40	176	100	76	43.18
3	0, 7	26	66	290	192	98	33.79
4	1, 2	12	28	142	102	40	28.17
5	1, 3	22	54	256	190	66	25.78
6	2, 5	26	64	222	148	74	33.33
7	3, 4	24	60	216	140	76	35.19
8	3, 9	28	72	310	196	114	36.77
9	4, 5	24	58	242	154	88	36.36
10	4, 6	14	32	180	116	64	35.56
11	5, 8	20	48	242	142	100	41.32
12	5, 11	24	58	228	152	76	33.33
13	6, 7	16	38	208	128	80	38.46
14	7, 10	28	70	252	200	52	20.63
15	8, 10	14	30	166	138	28	16.87
16	9, 12	20	48	198	132	66	33.33
17	9, 13	10	22	130	72	58	44.62
18	10, 12	22	54	214	174	40	18.69
19	10, 13	10	22	86	70	16	18.60
20	11, 12	12	26	106	66	40	37.74
21	11, 13	6	12	78	66	12	15.38

Table 6-5 Results of RLB for Net2 with H-L Model

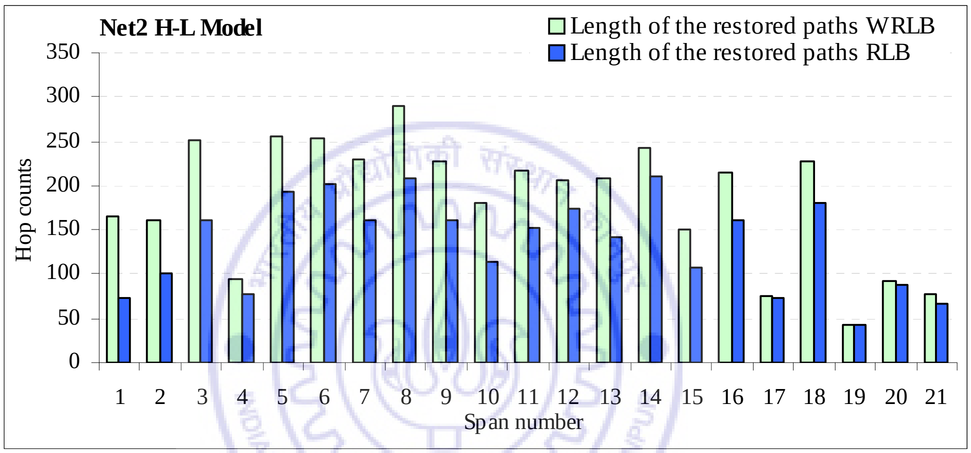
Net2 (Total spare capacity T_{sp} = 286)							
RLB with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	166	72	94	56.63
2	0, 2	16	40	160	100	60	37.50
3	0, 7	26	66	252	162	90	35.71
4	1, 2	12	28	94	78	16	17.02
5	1, 3	22	54	256	194	62	24.22
6	2, 5	26	64	254	202	52	20.47
7	3, 4	24	60	230	162	68	29.57
8	3, 9	28	72	290	208	82	28.28
9	4, 5	24	58	228	160	68	29.82
10	4, 6	14	32	180	114	66	36.67
11	5, 8	20	48	216	152	64	29.63
12	5, 11	24	58	206	174	32	15.53
13	6, 7	16	38	208	142	66	31.73
14	7, 10	28	70	242	210	32	13.22
15	8, 10	14	30	150	108	42	28.00
16	9, 12	20	48	214	160	54	25.23
17	9, 13	10	22	76	72	4	5.26
18	10, 12	22	54	228	180	48	21.05
19	10, 13	10	22	42	42	0	0.00
20	11, 12	12	26	92	88	4	4.35
21	11, 13	6	12	78	66	12	15.38

Table 6-6 Results of RLB for Net2 with DCPC Model

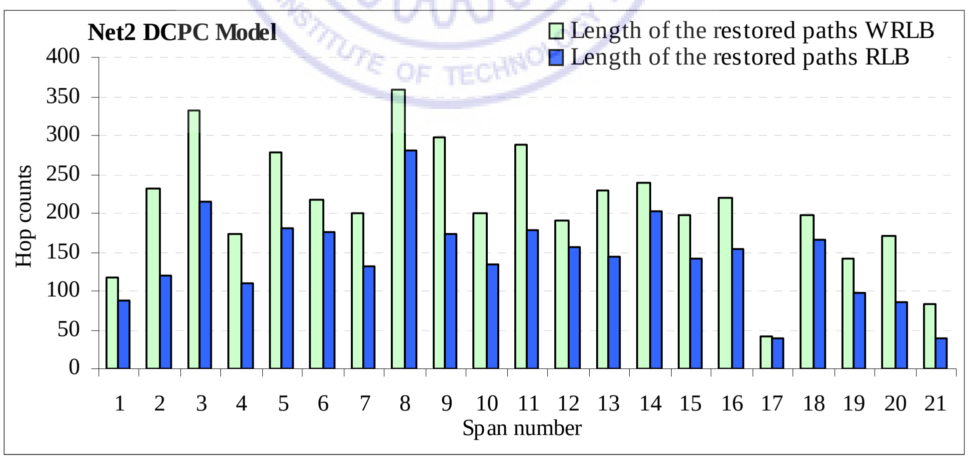
Net2 (Total spare capacity T_{sp} = 362)							
RLB with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	116	88	28	24.14
2	0, 2	16	40	232	120	112	48.28
3	0, 7	26	66	332	214	118	35.54
4	1, 2	12	28	172	110	62	36.05
5	1, 3	22	54	278	180	98	35.25
6	2, 5	26	64	216	176	40	18.52
7	3, 4	24	60	200	132	68	34.00
8	3, 9	28	72	358	280	78	21.79
9	4, 5	24	58	298	174	124	41.61
10	4, 6	14	32	200	134	66	33.00
11	5, 8	20	48	288	178	110	38.19
12	5, 11	24	58	190	156	34	17.89
13	6, 7	16	38	230	144	86	37.39
14	7, 10	28	70	238	202	36	15.13
15	8, 10	14	30	198	142	56	28.28
16	9, 12	20	48	220	154	66	30.00
17	9, 13	10	22	42	38	4	9.52
18	10, 12	22	54	198	166	32	16.16
19	10, 13	10	22	142	98	44	30.99
20	11, 12	12	26	170	86	84	49.41
21	11, 13	6	12	84	40	44	52.38



(a)



(b)



(c)

Figure 6-7 Length of the restored paths without RLB and with RLB for Net2

Table 6-7 Results of RLB for Net3 with SCO Model

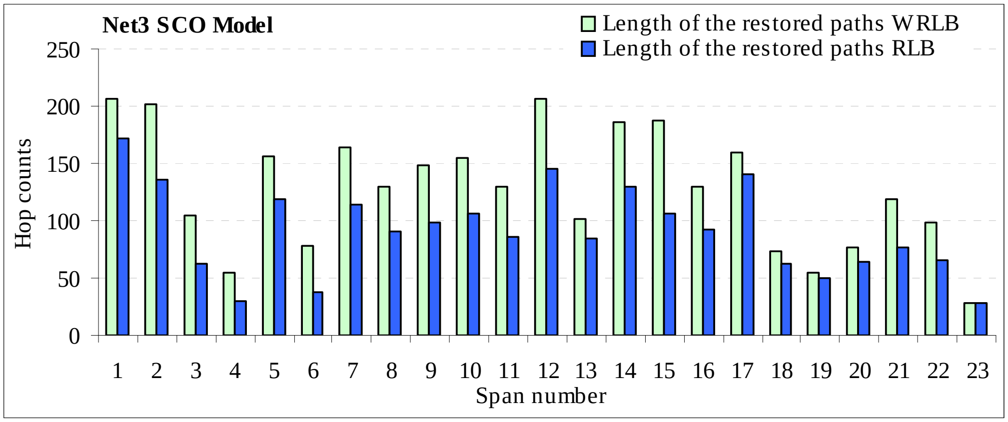
Net3 (Total spare capacity T_{sp} = 194)							
RLB with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	206	172	34	16.50
2	0, 8	22	56	202	136	66	32.67
3	0, 11	8	16	104	62	42	40.38
4	0, 12	6	10	54	30	24	44.44
5	1, 2	14	32	156	118	38	24.36
6	1, 9	6	12	78	38	40	51.28
7	2, 3	18	46	164	114	50	30.49
8	2, 9	16	42	130	90	40	30.77
9	2, 10	16	38	148	98	50	33.78
10	3, 4	14	36	154	106	48	31.17
11	3, 10	12	26	130	86	44	33.85
12	4, 5	20	52	206	146	60	29.13
13	4, 10	14	32	102	84	18	17.65
14	5, 6	16	40	186	130	56	30.11
15	6, 7	16	42	188	106	82	43.62
16	6, 8	20	50	130	92	38	29.23
17	6, 10	24	60	160	140	20	12.50
18	7, 8	8	16	74	62	12	16.22
19	8, 11	6	10	54	50	4	7.41
20	9, 12	6	10	76	64	12	15.79
21	10, 11	14	30	118	76	42	35.59
22	10, 12	12	26	98	66	32	32.65
23	11, 12	4	6	28	28	0	0.00

Table 6-8 Results of RLB for Net3 with H-L Model

Net3 (Total spare capacity T_{sp} = 194)							
RLB with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	206	146	60	29.13
2	0, 8	22	56	202	134	68	33.66
3	0, 11	8	16	102	76	26	25.49
4	0, 12	6	10	52	28	24	46.15
5	1, 2	14	32	156	98	58	37.18
6	1, 9	6	12	76	34	42	55.26
7	2, 3	18	46	172	118	54	31.40
8	2, 9	16	42	128	74	54	42.19
9	2, 10	16	38	134	102	32	23.88
10	3, 4	14	36	118	88	30	25.42
11	3, 10	12	26	124	74	50	40.32
12	4, 5	20	52	206	142	64	31.07
13	4, 10	14	32	110	84	26	23.64
14	5, 6	16	40	186	130	56	30.11
15	6, 7	16	42	188	106	82	43.62
16	6, 8	20	50	90	90	0	0.00
17	6, 10	24	60	178	136	42	23.60
18	7, 8	8	16	76	64	12	15.79
19	8, 11	6	10	52	48	4	7.69
20	9, 12	6	10	74	62	12	16.22
21	10, 11	14	30	116	80	36	31.03
22	10, 12	12	26	96	76	20	20.83
23	11, 12	4	6	10	10	0	0.00

Table 6-9 Results of RLB for Net3 with DCPC Model

Net3 (Total spare capacity T_{sp} = 250)							
RLB with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	212	178	34	16.04
2	0, 8	22	56	208	148	60	28.85
3	0, 11	8	16	104	64	40	38.46
4	0, 12	6	10	54	30	24	44.44
5	1, 2	14	32	168	116	52	30.95
6	1, 9	6	12	78	38	40	51.28
7	2, 3	18	46	142	108	34	23.94
8	2, 9	16	42	130	98	32	24.62
9	2, 10	16	38	142	92	50	35.21
10	3, 4	14	36	140	98	42	30.00
11	3, 10	12	26	130	90	40	30.77
12	4, 5	20	52	234	172	62	26.50
13	4, 10	14	32	122	76	46	37.70
14	5, 6	16	40	192	130	62	32.29
15	6, 7	16	42	194	118	76	39.18
16	6, 8	20	50	142	116	26	18.31
17	6, 10	24	60	172	132	40	23.26
18	7, 8	8	16	104	82	22	21.15
19	8, 11	6	10	54	50	4	7.41
20	9, 12	6	10	76	64	12	15.79
21	10, 11	14	30	118	94	24	20.34
22	10, 12	12	26	98	60	38	38.78
23	11, 12	4	6	28	28	0	0.00



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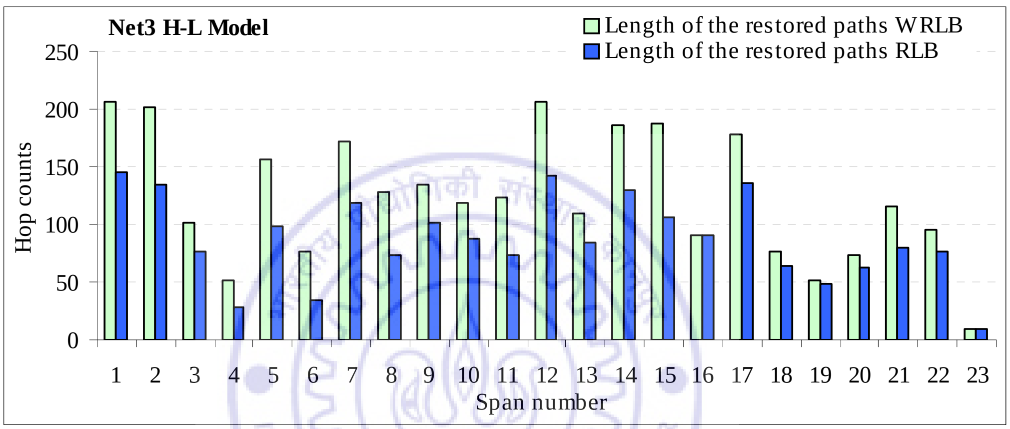

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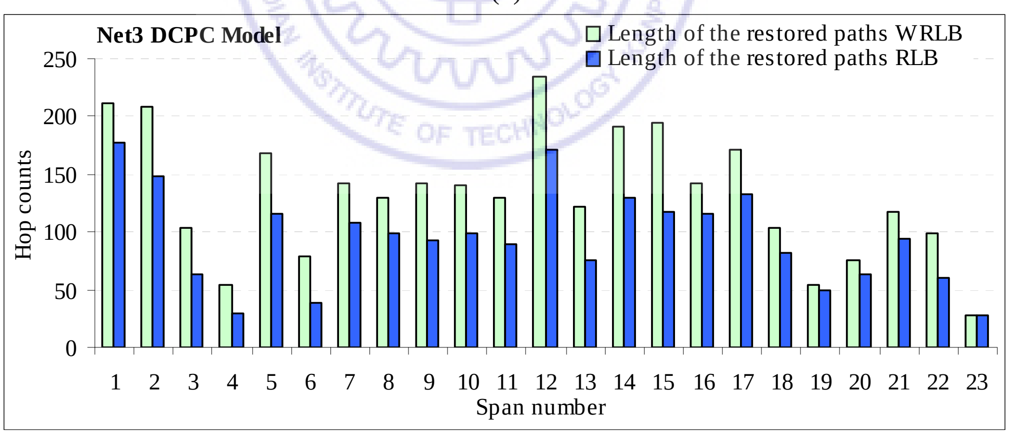


(c)

Figure 6-8 Length of the restored paths without RLB and with RLB for Net3

Table 6-10 Results of RLB for Net4 with SCO Model

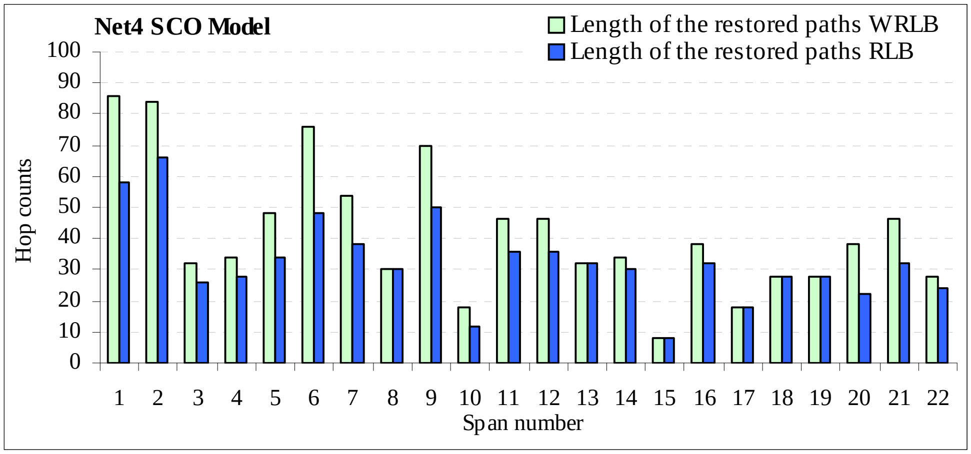
Net4 (Total spare capacity T_{sp} = 70)							
RLB with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	58	28	32.56
2	0, 2	14	30	84	66	18	21.43
3	0, 3	6	10	32	26	6	18.75
4	0, 4	4	6	34	28	6	17.65
5	1, 3	6	10	48	34	14	29.17
6	1, 7	10	22	76	48	28	36.84
7	2, 4	6	10	54	38	16	29.63
8	2, 6	6	10	30	30	0	0.00
9	2, 8	8	16	70	50	20	28.57
10	3, 4	4	6	18	12	6	33.33
11	3, 5	8	14	46	36	10	21.74
12	3, 6	8	14	46	36	10	21.74
13	3, 7	6	10	32	32	0	0.00
14	4, 5	6	10	34	30	4	11.76
15	4, 6	2	2	8	8	0	0.00
16	5, 6	4	6	38	32	6	15.79
17	5, 7	2	2	18	18	0	0.00
18	5, 9	6	10	28	28	0	0.00
19	6, 8	6	10	28	28	0	0.00
20	6, 9	4	6	38	22	16	42.11
21	7, 9	8	16	46	32	14	30.43
22	8, 9	4	6	28	24	4	14.29

Table 6-11 Results of RLB for Net4 with H-L Model

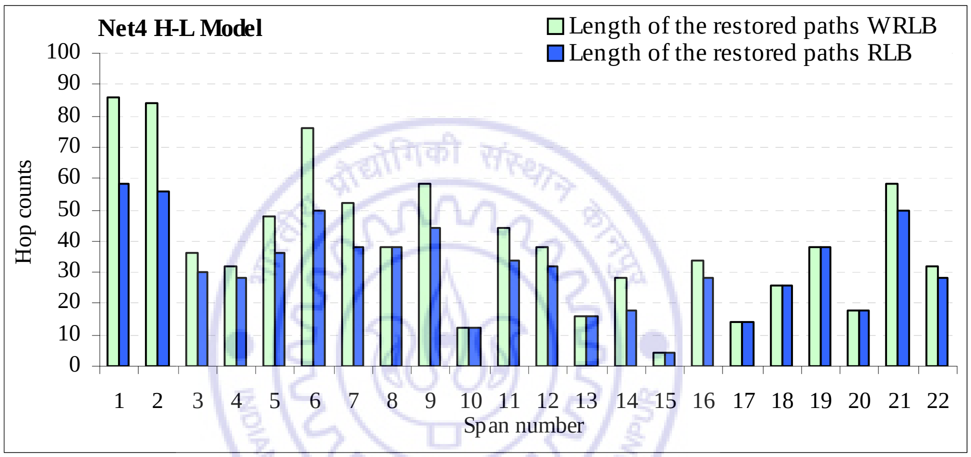
Net4 (Total spare capacity T_{sp} = 70)							
RLB with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	58	28	32.56
2	0, 2	14	30	84	56	28	33.33
3	0, 3	6	10	36	30	6	16.67
4	0, 4	4	6	32	28	4	12.50
5	1, 3	6	10	48	36	12	25.00
6	1, 7	10	22	76	50	26	34.21
7	2, 4	6	10	52	38	14	26.92
8	2, 6	6	10	38	38	0	0.00
9	2, 8	8	16	58	44	14	24.14
10	3, 4	4	6	12	12	0	0.00
11	3, 5	8	14	44	34	10	22.73
12	3, 6	8	14	38	32	6	15.79
13	3, 7	6	10	16	16	0	0.00
14	4, 5	6	10	28	18	10	35.71
15	4, 6	2	2	4	4	0	0.00
16	5, 6	4	6	34	28	6	17.65
17	5, 7	2	2	14	14	0	0.00
18	5, 9	6	10	26	26	0	0.00
19	6, 8	6	10	38	38	0	0.00
20	6, 9	4	6	18	18	0	0.00
21	7, 9	8	16	58	50	8	13.79
22	8, 9	4	6	32	28	4	12.50

Table 6-12 Results of RLB for Net4 with DCPC Model

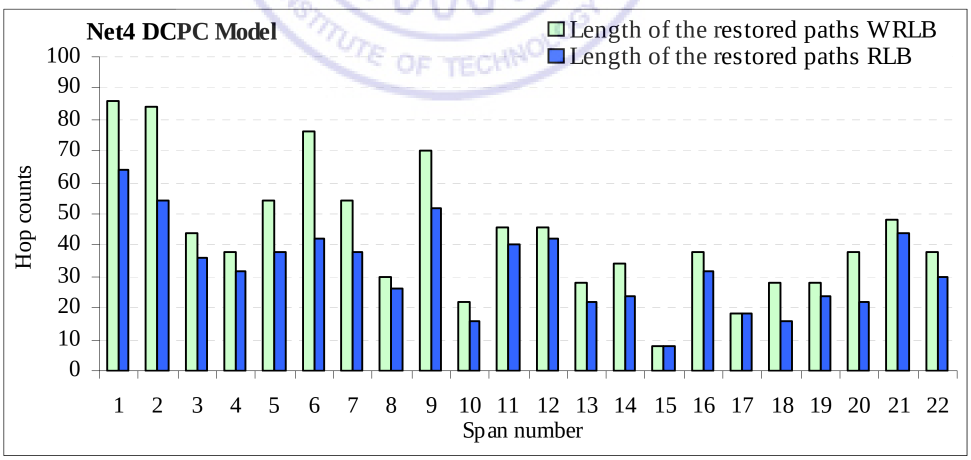
Net4 (Total spare capacity T_{sp} = 70)							
RLB with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLB	Length of the restored paths RLB	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	64	22	25.58
2	0, 2	14	30	84	54	30	35.71
3	0, 3	6	10	44	36	8	18.18
4	0, 4	4	6	38	32	6	15.79
5	1, 3	6	10	54	38	16	29.63
6	1, 7	10	22	76	42	34	44.74
7	2, 4	6	10	54	38	16	29.63
8	2, 6	6	10	30	26	4	13.33
9	2, 8	8	16	70	52	18	25.71
10	3, 4	4	6	22	16	6	27.27
11	3, 5	8	14	46	40	6	13.04
12	3, 6	8	14	46	42	4	8.70
13	3, 7	6	10	28	22	6	21.43
14	4, 5	6	10	34	24	10	29.41
15	4, 6	2	2	8	8	0	0.00
16	5, 6	4	6	38	32	6	15.79
17	5, 7	2	2	18	18	0	0.00
18	5, 9	6	10	28	16	12	42.86
19	6, 8	6	10	28	24	4	14.29
20	6, 9	4	6	38	22	16	42.11
21	7, 9	8	16	48	44	4	8.33
22	8, 9	4	6	38	30	8	21.05



(a)



(b)



(c)

Figure 6-9 Length of the restored paths without RLB and with RLB for Net4

Table 6-13 Effect of RLB with SCO, H-L and DCPC methods

Test Networks	Average Length of *p*-cycle	Average Length of working paths	L_{WRLB}	L_{RLB}	L_{WRLB} - L_{RLB}	Percent Reduction
Net1						
SCO	15.08	2.88	14.16	9.14	5.02	35.48
H-L	15.08		14.08	9.08	5.00	35.52
DCPC	15.90		15.82	9.66	6.16	38.91
Net2						
SCO	11.92	2.14	10.41	7.08	3.33	31.99
H-L	11.00		9.90	7.30	2.61	26.31
DCPC	12.07		11.29	7.72	3.56	31.58
Net3						
SCO	9.70	2.03	9.32	6.63	2.70	28.92
H-L	9.70		9.03	6.33	2.70	29.87
DCPC	10.42		9.63	6.91	2.72	28.27
Net4						
SCO	8.75	1.58	6.49	5.04	1.45	22.34
H-L	8.75		6.14	4.90	1.24	20.18
DCPC	8.75		6.73	5.07	1.66	24.69

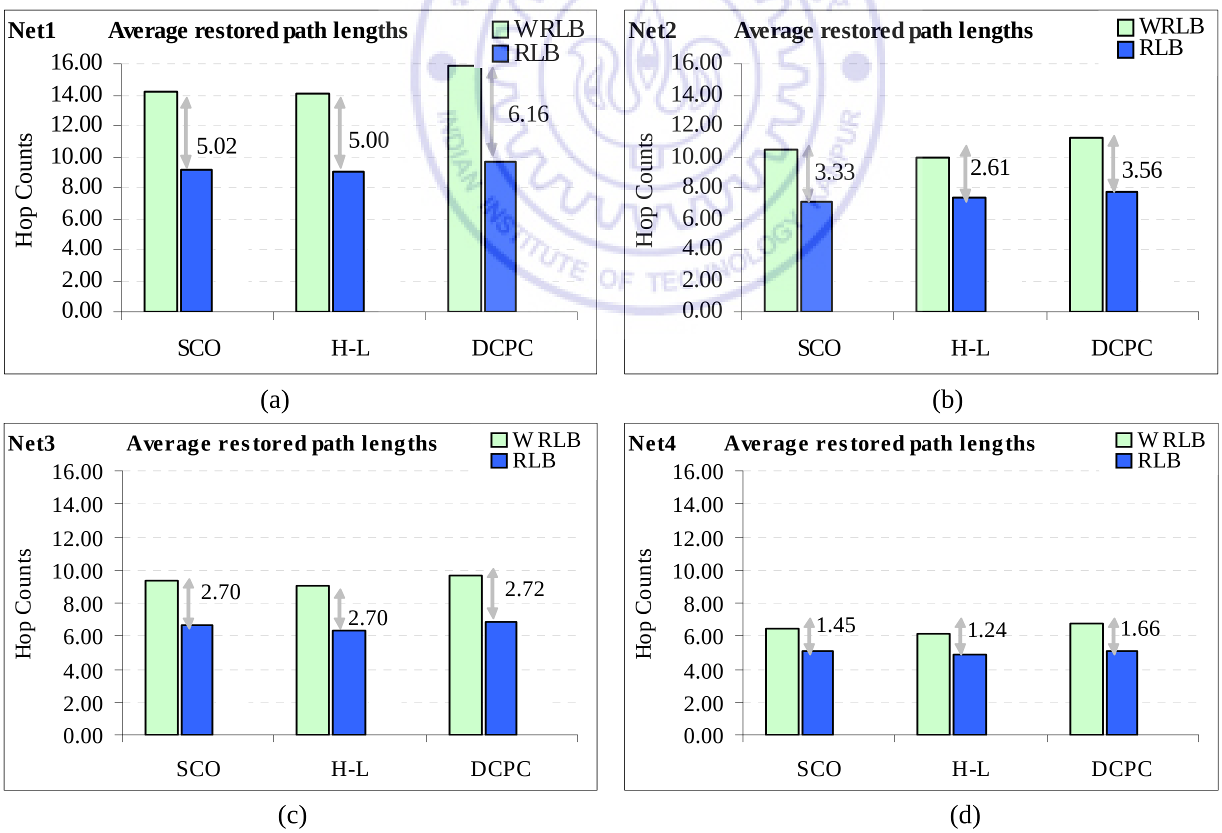


Figure 6-10 Effect of RLB with SCO, H-L and DCPC methods

- ***DISCUSSIONS***

The restored paths without RLB, for some spans, have consumed a large fraction of the spare capacity used to form the *p*-cycles e.g. for Net1 – span nos. 1, 3, 14, 15, 16, 17, for Net2 – span nos. 3, 5, 8, for Net3 – span nos. 1, 2, 12, and for Net4 – span nos. 1, 2. The reduction in the restored path length is also significant for these spans. In some cases the reduction is more than 50% e.g. (Net1 – Table 6.1 – span no. 1, Table 6.3 – span no. 2, 15, 16; Net2 – Table 6.5 – span no. 1 Table 6.6 – span no. 22; Net3 – Table 6.7 – span no. 6) . The reduction in absolute terms is also very significant. The maximum amount is in the range of 30% to 58% of the total spare capacity (highlighted with blue colour). The average reduction as shown in Table 6.13 with all the models is also about 30% for all the test networks except Net4, for which, it is in the range of 20%. The Net4 is SmallNet with large $\overline{d}$, hence, the reduction is less. The above observations indicate that the effects of RLB can not be ignored.

If for the links of a span, after restoration with a set of *p*-cycles, there is no loop back then the reduction will obviously be zero. These type of spans are minimum for Net1 and Net2, as for these networks, n , the total number of nodes is large and the average path length is more (Table 6.13); therefore, more loop backs are expected. Whereas in Net4 the grey spans are maximum due to two reasons – one n is relatively lower and second – $\overline{d}$ is maximum hence, average path lengths are small resulting in lesser loop backs. It may also be noted that for single hop working paths there will not be any loop back with any *p*-cycle, hence, reduction in restored path lengths will be zero for these paths. Further, the grey rows are maximum with H-L model. This is due to the fact that with this model, for every span the solution set of *p*-cycles is not same, whereas with SCO and DCPC model the same set of *p*-cycles is used for all the spans. In the H-L model, for every span, the solution set of the *p*-cycles are found separately with additional constraint in the form of hop count limit which limits the restored path lengths, hence, more spans without loop backs are there in this model.

The spans, for which the reduction in the restored path length is zero, are not same for the three models of *p*-cycle formation (Tables 6.1 to 6.12). Similarly spans, for which reduction in restored path length is maximum, are not same for all the three models. Same is true for spans for which reduction in the restored path length is maximum percent wise. The spans with maximum reduction, either absolute or percent, are also not fixed. The working paths are fixed for all the three cases; the only change is in the solution set of *p*-cycles. The *p*-cycles, in the solution sets of SCO, H-L and DCPC model, are different. This suggests that the amount of loop backs depends upon the *p*-cycles which are protecting a particular path.

The order of maximum reduction (blue and green lines in the Tables 6.1 to 6.12) and the difference in L_{WRLB} and L_{RLB} is almost same for a particular network with SCO and H-L model, but is slightly higher for DCPC. The amount is increasing with n. In case of SCO and H-L model, the total spare capacity used by *p*-cycles, T_{sp} is same (Tables 6.1 and 6.2, Tables 6.4 and 6.5, Tables 6.7 and 6.8, and Tables 6.10.and 6.11 for Net1 to Net4 respectively). The average length of *p*-cycles is also same (Table 6.13). However, in case of DCPC, T_{sp} is more and the average length of *p*-cycles is also more, except for Net4 in which the T_{sp} is same for all the cases and average length of *p*-cycles is also same. However, the percentage reduction in the restored path lengths for Net4, is not same for all the models and is maximum with DCPC model (Table 6.13). Further, the behavior of percentage reduction is not consistent. This suggests that some other factors are also there which are influencing the behavior of percentage reduction. With further study, we have found that allocation of a *p*-cycle to a path in failed span is also important and may be responsible for the inconsistency. This will be discussed in detail in the next chapter.

6.5.3 EFFECTIVENESS WITH HOP COUNT LIMITED MODEL

In the previous section, we have taken fixed hop count limit for the purpose of comparison with other methods of *p*-cycle formation. To study the effect of hop count limit, the L_{WRLB} and L_{RLB} are calculated for different values of hop count limits. The results are shown in Fig. 6.11. For smaller values of hop count limit, the restored path lengths are small, and reduction in the restored path length with RLB is very small. This is due to the fact that with hop count limits, the restoration paths provided by *p*-cycles are less than or equal to the hop count limit. For smaller hop count limit the restoration paths are smaller, hence there is almost no loop backs. However for these cases, the initial spare capacity required for the formation of the set of *p*-cycles is quite large (Fig. 6.12). Therefore, to achieve the smaller restored path lengths, initially more spare capacity is to be provisioned. For higher hop count limits approaching to the number of nodes in the network, the spare capacity required for the formation of the set of *p*-cycles approaches to that of the SCO model. With increase in the hop count limit, the values of L_{WRLB} and L_{RLB} also increases and matches with that of the SCO model. This further strengthens our argument of loop backs and longer restored path lengths, the price paid for mesh like efficiency of *p*-cycles. Thus, with efficient *p*-cycles, restored paths will be longer resulting in more loop backs, and making RLB more effective. If smaller *p*-cycles are used, obviously, restored paths will be shorter with less loop backs, but with more initial spare capacity. Whereas with RLB, smaller restored path lengths can be obtained with optimum initial spare capacity.

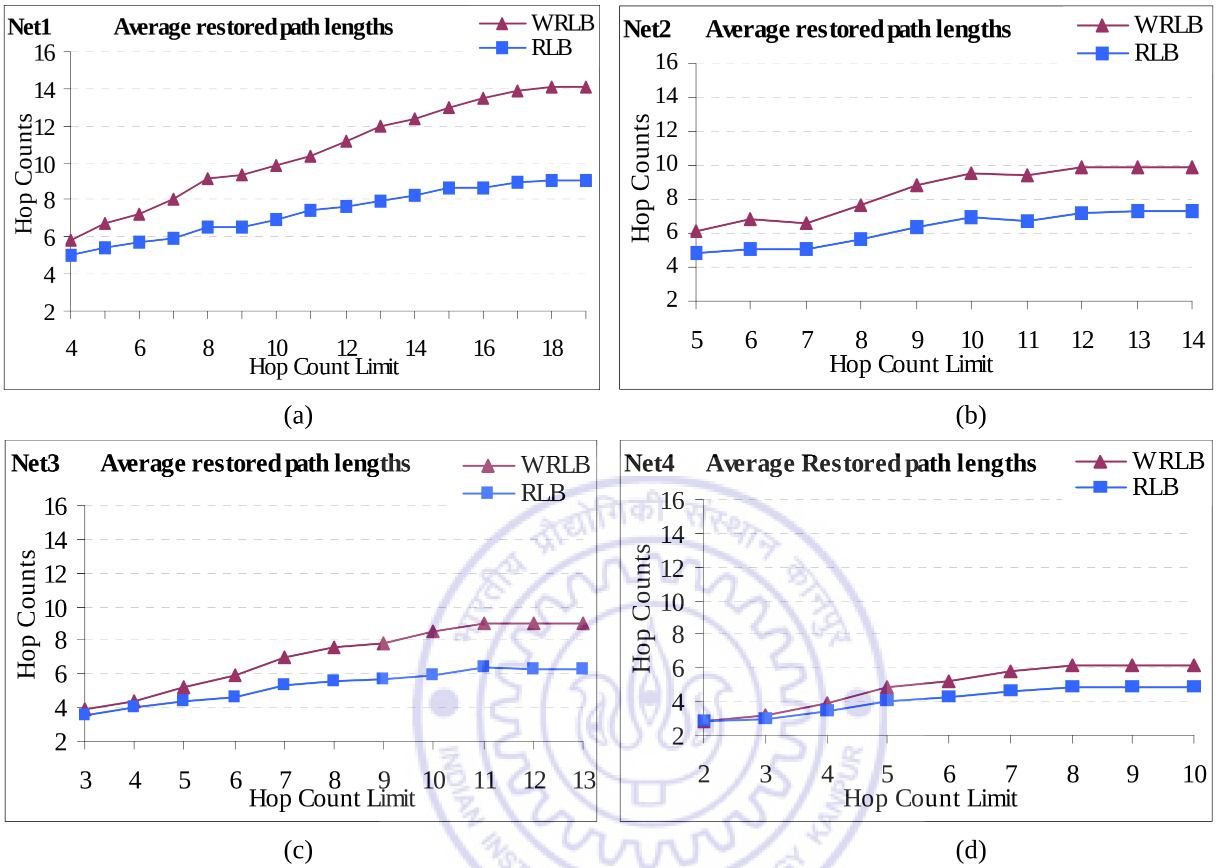


Figure 6-11 **Variation in effects of RLB with varying hop count limit**

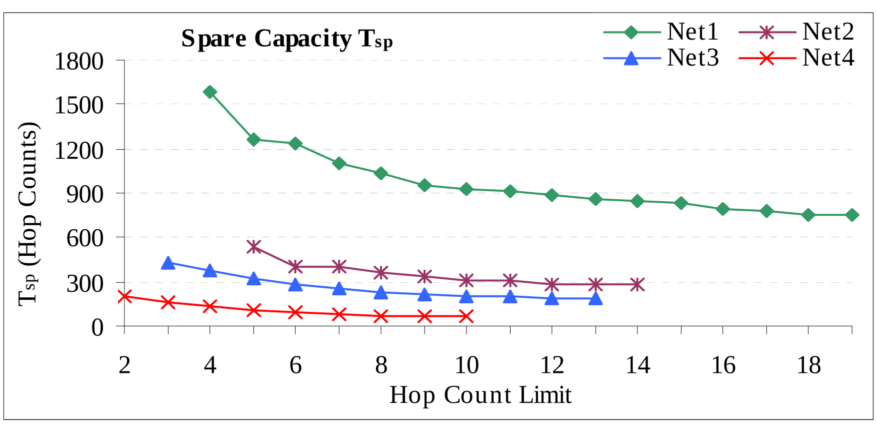


Figure 6-12 **Variations in T_{sp} with varying hop count limit**

6.5.4 *EFFECTIVENESS WITH AVERAGE NODAL DEGREE*

To consider the effect of $\bar{d}$ on the amount of released capacity we have tested the algorithm with decreasing $\bar{d}$ for Net4, for SCO model which optimizes the initial spare capacity. To decrease the $\bar{d}$, spans are removed randomly. Only those spans have been removed which left the network with a feasible ILP solution. The simulations were done many times with different random seeds, and average is taken for all the simulations (Fig. 6.13).

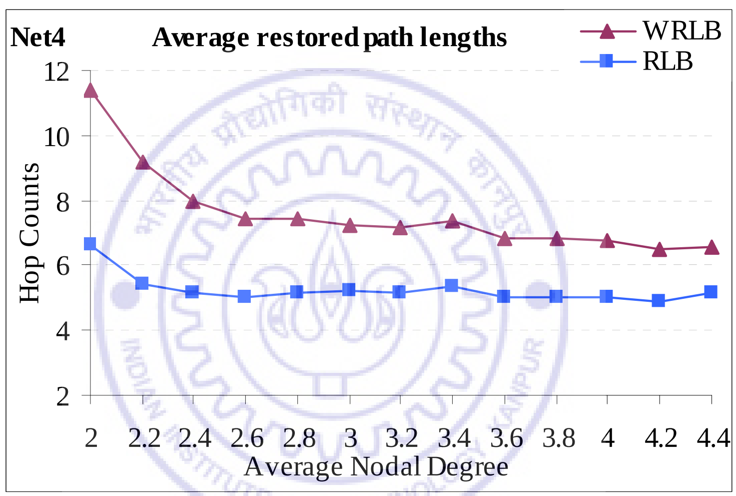


Figure 6-13 Effects of RLB with varying average nodal degree

The L_{RLB} values remain almost constant for $\bar{d}$ in the range of 2.2 to 4.4. Whereas, there is reduction in the L_{WRLB}. Hence, the difference in L_{WRLB} and L_{RLB} is small for higher values of $\bar{d}$, and is increasing as $\bar{d}$ is reduced. It means that loop backs are less for larger values of $\bar{d}$, and more for smaller $\bar{d}$. This is also expected intuitively.

6.5.5 RLB WITH NUMBER OF NODES IN THE NETWORK

Similarly, the simulations are carried out for constant $\overline{d}$ and increasing n (Fig. 6.14). The L_{WRLB} and L_{RLB} have been found for $\overline{d}$ = 2.0, 3.0 and 4.0 (Fig. 6.14 (a), (b) and (c)). The values of L_{WRLB} and L_{RLB} for $\overline{d}$ = 2.0 are in perfect agreement with the L_{WRLB} and L_{RLB} values obtained mathematically from Equations 6.3 and 6.4. The Equations 6.3 and 6.4 have been derived without any assumptions; hence, theoretical and simulated values are exactly same, thus validating the simulations.

The values of L_{WRLB} and L_{RLB} are increasing linearly with increase in n for all the values of $\overline{d}$ (Fig. 6.14). The lines for L_{WRLB} are more steep as compared to L_{RLB}. This indicates the increase in the amount of loop backs. The steepness of L_{WRLB} and L_{RLB} are inversely proportional to $\overline{d}$. Thus we can say that with increase in $\overline{d}$ the amount of loop backs is decreasing (same as obtained with Net4 in section 6.5.2).

The reduction in the restored path lengths i.e. the difference between L_{WRLB} and L_{RLB} is shown in Fig 6.15 for all the values of $\overline{d}$. The difference is almost linearly increasing with increase in n, however, again the steepness of the difference is decreasing with increase in $\overline{d}$. It means that loop backs are increasing with n and decreasing with $\overline{d}$. The result for n is in confirmation with the mathematical bound. The reduction will become equal to zero for $\overline{d} = n-1$ which is the limiting case, when there will be no loop backs and L_{RLB} remains equal to L_{WRLB}.

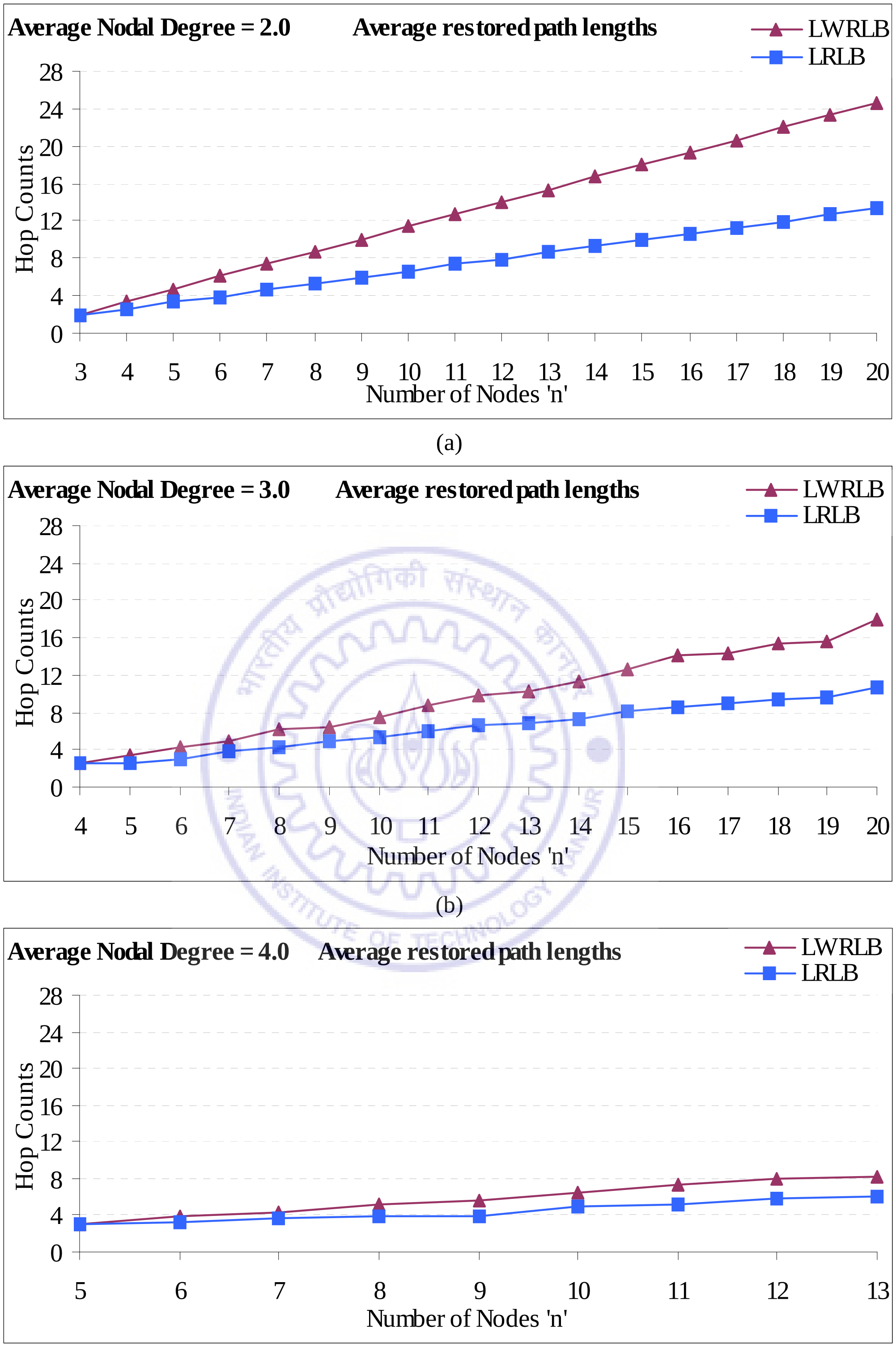


Figure 6-14 **Variations in** L_{WRLB} **and** L_{RLB} **with number of nodes for constant** $\overline{d}$

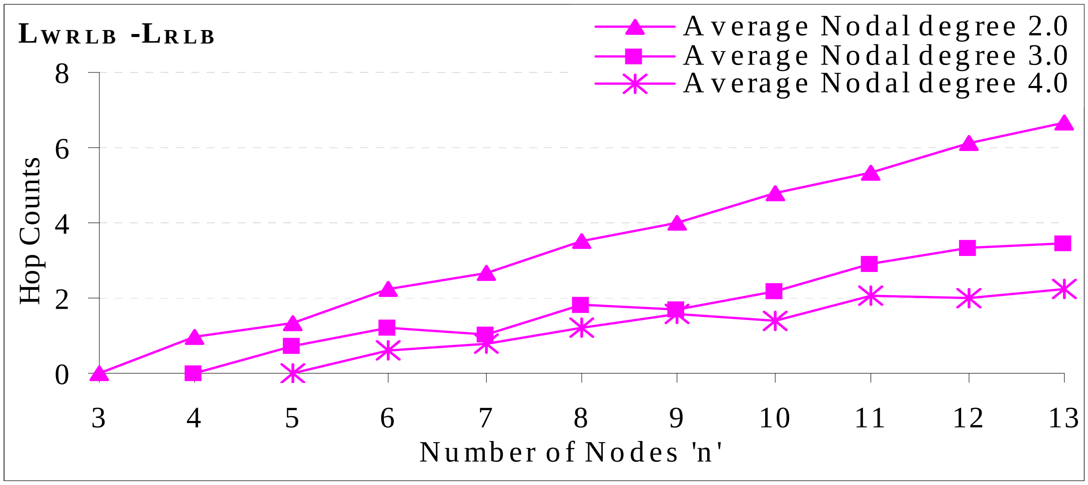
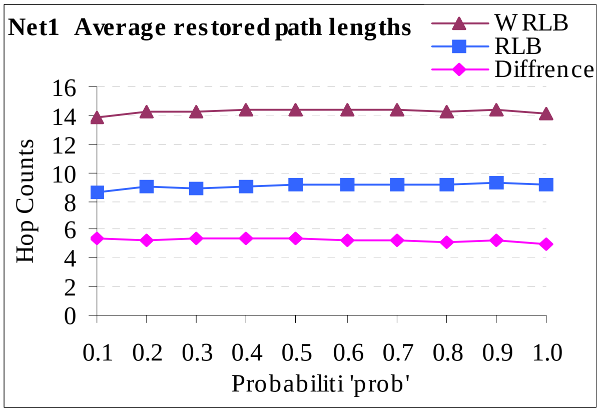


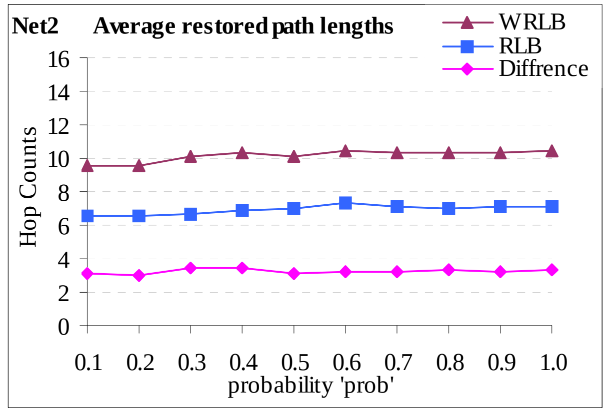
Figure 6-15 Difference in L_{WRLB} and L_{RLB} for different values of $\overline{d}$

6.5.6 RESULT WITH VARIOUS TRAFFIC DISTRIBUTIONS

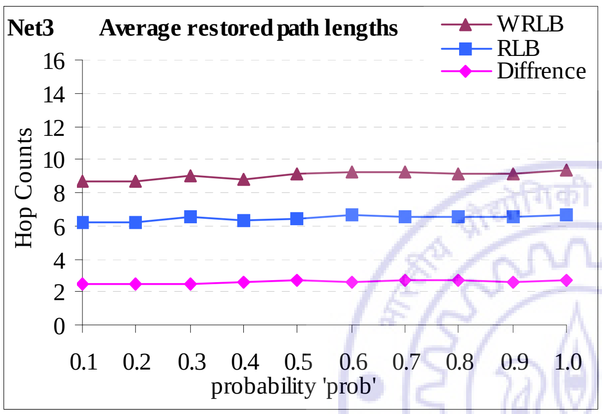
We have further considered the general case of traffic matrix when the traffic from one node is generated with probability ‘prob’ for every other node in the network and values of ‘prob’ are taken as 0.1, 0.2,...,1.0. With each value of ‘prob’, the traffic matrix is generated and *p*-cycles are found with SCO model. The L_{WRLB} and L_{RLB} are calculated. For each value of ‘prob’, the process is repeated many times and average is taken to remove the estimation noise from simulations. The results are shown in Fig. 6.16. The difference between L_{WRLB} and L_{RLB} remains almost constant. Thus we can say that reduction is almost independent of the traffic load.



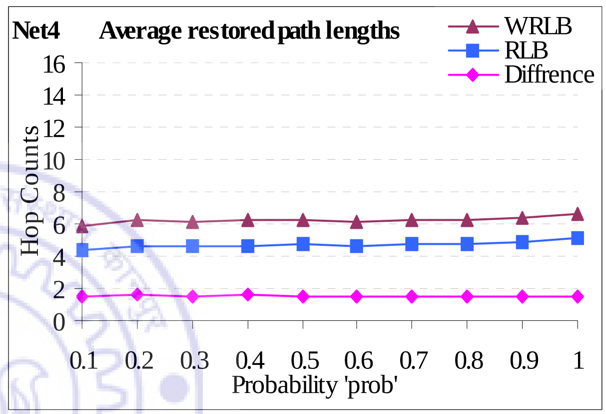
(a)



(b)



(c)



(d)

Figure 6-16 **The L_{WRLB}, L_{RLB} and L_{WRLB} - L_{RLB} (difference) values for (a) Net1, (b) Net2, (c) Net3 and (d) Net4 with various traffic distributions**

6.5.7 EFFECTIVENESS IN CASE OF DUAL FAILURE SURVIVABILITY

The RLB provides significant reduction in the restored path lengths. The reduction in the restored path lengths means release of redundant capacity, in some cases as much as 38.9% (Net1 –Table 6.13). The additional released capacity with RLB can be used for providing protection in the event of second failure. The effect on survivability for dual failures has been observed in the following two ways.

- ***EFFECT ON RESTORATION OF LINKS DURING SECOND FAILURE***

The total number of links which can be protected against second failure with RLB and WRLB have been compared. The network is provisioned with initial spare capacity as obtained in the SCO model. Following steps are used for calculating the percentage of links which can be protected against second failure.

Step 1- Failure of any one span is assumed, all the paths passing through that span has been restored with RLB and WRLB.

Step 2- The working capacity of all the remaining spans has been modified to include the capacity used by the restored paths of the failed span with RLB and WRLB.

Step 3- The spare capacity is also modified to remove the capacity used for restoration of the paths of the failed span with RLB and WRLB and the capacity which is released from RLB is added to the spare capacity.

Step 4- The DCPC method is used to form the *p*-cycles in the spare capacity, and the number of links which can be protected by the formed set of *p*-cycles is counted with RLB and WRLB.

Step 5- Step 1 to step 4 are repeated for each span and then average is taken to find out the percentage of links that can be protected against second failure with RLB and WRLB.

The results are shown in Fig. 6.17. The results show the improvement in the percentage of links that can be provided protection with RLB in the event of second failure. For all the networks, with RLB, more number of links can be protected against second failure with the same amount of initial spare capacity and the maximum improvement 14.4%, is for test network, Net1, i.e. 14.4% more links can be restored in the event of second failure with RLB as compared to WRLB.

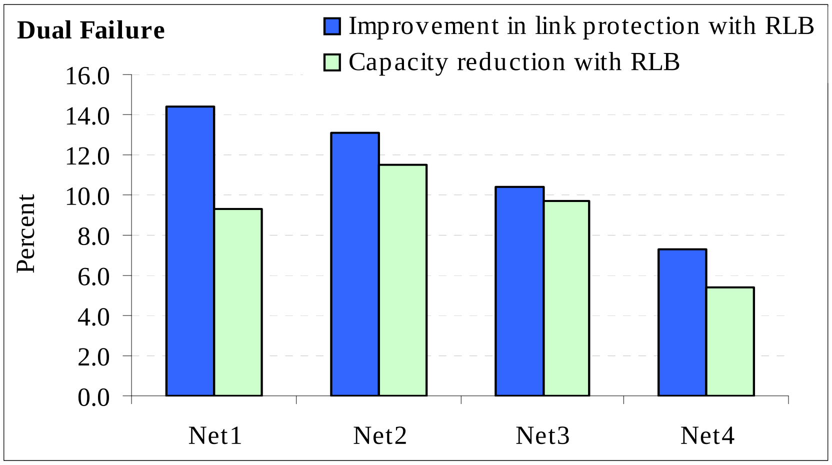


Figure 6-17 Percent improvement in the link protection against second failure and reduction in the spare capacity required for 100% dual failure restorability with RLB over WRLB

- ***REQUIREMENT OF SPARE CAPACITY FOR SECOND FAILURE RESTORABILITY***

In this case, after step 1 and step 2, SCO model is used to find the total amount of spare capacity for 100% dual failure restorability with RLB and WRLB. With this model, we have the values of required spare capacity on each span (after failure of a span) for 100% protection during second failure. The above process is repeated for each span of the network considering it as a failed span and then the maximum capacity value required on every span is taken for 100% dual failure restorability with RLB and WRLB.

The percentage reduction in the amount of initial spare capacity to be provisioned with RLB has also been shown in Fig. 6.17. With RLB for all the test networks the amount of initial capacity to be provisioned for 100% restorability, is smaller. The maximum improvement is obtained for Net 2, about 11%. It means, initially 11% less capacity is to be provisioned in the network to provide dual failure survivability.

6.6 CONCLUSIONS

The effectiveness of RLB has been studied extensively in this chapter. We have found that amount of loop backs or reduction in the restored path lengths is significant and remains almost constant for a particular network under various test conditions with SCO model. The reduction depends upon the length of the protection path provided by the *p*-cycles. Therefore, with H-L model for smaller hop count limits, loop backs are very small but with large amount of initial spare capacity. However, with hop count limit above a threshold value, when spare capacity requirement matches with that of SCO model, the reduction with H-L model is more or less same as with SCO model. Similarly with DCPC, loop backs are more as the length of the protection path provided by *p*-cycle is relatively more with more initial spare capacity and hence, more reduction.

We have also found that the reduction in the restored path lengths is directly proportional to the number of nodes n in the network as derived mathematically also. The reduction in the restored path lengths is inversely proportional to average nodal degree $\overline{d}$. Also, with various traffic distributions, the amount of reduction in the restored path lengths remains constant. With RLB, there is definite improvement in the dual failure restorability also.

Another interesting fact is that apart from the dependency on the factors discussed above there is some other factor also on which the reduction in the restored path lengths depends. As mentioned earlier, the reduction also depends on the mapping of a *p*-cycle to a working path in the span. This issue has been investigated in the next Chapter.

In the next chapter, we present the effects of *p*-cycle allocation and due to the importance of RLB a distributed protocol to implement RLB in real network is also given.

CHAPTER 7
DISTRIBUTED PROTOCOL AND OPA[12]

In this chapter, the distributed protocol for the removal of loop backs and reconfiguration of the restored paths, is given. With this protocol, the loop backs in the restored path are first identified and then removed. The protocol can be implemented in any real network in a distributed manner. Next, the importance of allocation of *p*-cycles to the paths in the failed span has been discussed. The method for the allocation of *p*-cycles to protect a working path is given and its effect on the reduction of the restored path lengths has been studied.

7.1 DISTRIBUTED ALGORITHM FOR RLB

In this protocol, we have assumed that each node maintains the status table for each lightpath, consisting of previous node, next node, wavelength / fiber in the previous span, wavelength / fiber in next span. All the nodes are also maintaining status tables for all the configured *p*-cycles in the form of mapping from previous node and wavelength / fiber to next node and wavelength / fiber. For second phase reconfiguration, each lightpath has been identified with its PathId, and to communicate between nodes, three types of packets, ‘Probe,’ ‘Switch,’ and ‘Release’ have been used. All the packets will have first and second fields as follows.

[12] This chapter is based on the work submitted in [145], and to be published in [146].

- PacketId: This field will contain the information about the type of the packet i.e. it identifies whether packet is ‘Probe’, ‘Switch’ or ‘Release’.
- PathId: This field will contain the identification number of the path which is being restored via the *p*-cycle path and for this path, second phase reconfiguration is taking place by removal of loop backs.

The *Probe packets* will have third field as

- Route: In this field, the Ids of the nodes, through which Probe packet will pass, are added.

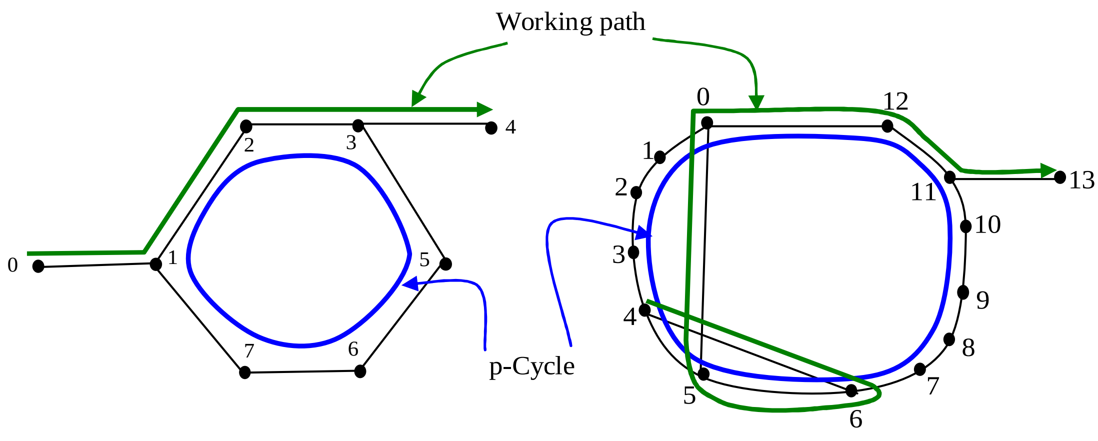
The *Switch packet* will have following additional fields.

- FirstNodeId: This field contains the Id of the node to which, the lightpath is going from the destination of Switch packet.
- SecondNodeId: This will contain the Id of the node to which, the lightpath is to be switched.

The *Release packet* will have the following additional fields;

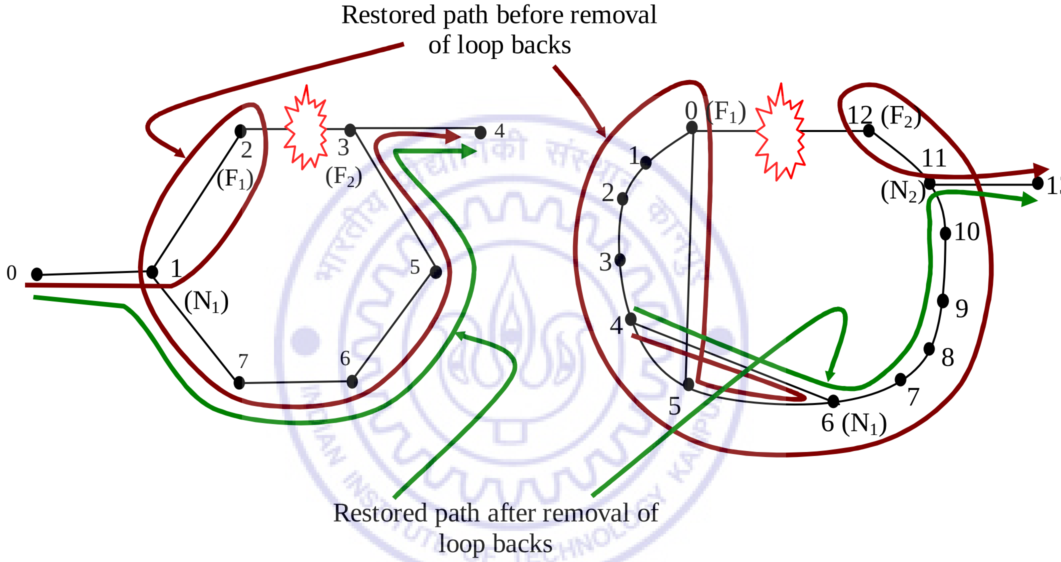
- ReleaseCap: When this field is set, the node through which the packet is passing will release the capacity (wavelength).
- NodeId: This field contains the Id of the common node which has generated this packet.
- DirectionFlag: Upstream or downstream forwarding.

The distributed protocol will be initiated at both the upstream and downstream nodes of the failed spans. Consider the network shown in Figs. 6.2 (a) and 6.3 (a) (reproduced on page 153). Let us call the upstream node 2, and the downstream node 3 of the failed span 2, 3, as F_1 and F_2 respectively. The algorithm will work as follows.



(a) (b)

Fig. 6.2 Working path and p-cycle



(a) (b)

Fig. 6.3 Restored path before and after removal of loop backs
(Reproduced here for convenience)

Step 1 is to collect the information about the route of the working path and the *p*-cycle path with 'Probe' packets by end nodes of the failed span. The F_1 (F_2) node will send 'Probe' packets to the source (destination) node via the upstream (downstream) nodes of the lightpath and to the F_2 (F_1) node through the restoration path provided by the *p*-cycle. Thus for each lightpath two 'Probe' packets will be sent by F_1 (F_2) node of the failed span.

Every node will enter its Id in the route field of the 'Probe' packet. When the packet reaches the source node (destination node) of the lightpath, then it is sent back to the F_1 (F_2) node of the failed span. This packet contains the route information of the working path from the source to the F_1 (F_2 to the destination) node. The F_1 (F_2) node will also receive the 'Probe' packet sent by the F_2 (F_1) node. This packet will contain the information of the restoration path provided by the *p*-cycle.

Step 2 is the identification of the common nodes with longest loop back lengths by end nodes of the failed span. As the F_1 (F_2) node will have the complete information of the working path from source to the F_1 (F_2 to the destination) node, and the restoration path of the *p*-cycle, it can identify the common nodes in the working path and the restoration path. Then, F_1 (F_2) will calculate the length of the loop backs for each of the common nodes and identify the loop back path having maximum length. The corresponding common node N1 (N2) is identified by F_1 (F_2).

Step 3 is to send the 'Switch' packets to the common nodes by end nodes of the failed span. The F_1 (F_2) node will send 'Switch' packet, to the identified common node N1 (N2).

Step 4 is to perform the switching action for removal of loop backs by the common node. The common node will identify the lightpath with its 'PathId' and perform the switching action to switch the lightpath from the node identified by the 'FirstNodeId' to the node identified by the 'SecondNodeId'. This will remove the loop back from the restored path.

Step 5 is to send the "Release' packet to the nodes involved in loop back for releasing the loop back capacity. The common node N1 (N2) will send the 'Release' packet to FirstNodeId. The FirstNodeId will release the capacity corresponding to the 'PathId' and send a similar request to next node in the downstream (upstream) direction. This chain of messages ultimately will arrive back at the common node N1 (N2) completing the release process.

This is to be noted that the capacity at the intermediate nodes of the loop back path will be released after the switching is performed at the identified common node, to maintain the continuity of the lightpath.

As an example to demonstrate how this protocol operates, consider the second phase reconfiguration in Fig. 6.2(b). The lightpath 4, 6, 5, 0, 12, 11, 13 is passing through 0, 12 (failed span). '0' and '12' are the upstream and downstream nodes of the failed span respectively. After the failure of the 0, 12 span, the lightpath is restored through the protection path 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 provided by the *p*-cycle (Fig. 6.3 (b)). This restoration is done by performing one switching action at each of the nodes 0 and 12 in the first phase. All the lightpaths passing through failed span 0, 12, will be restored in the same manner with the *p*-cycles of the solution set, during first phase. After this restoration, in the second phase, the node 0 (node 12) will send the Probe packets to source node 4 (destination node 13), and to 12 (0) through the protection path 0, 1, 2, ……., 11, 12 (12, 11, 10,……., 1, 0) provided by the *p*-cycle for the lightpath. The probe packets are sent back by source node 4 (destination node 13) to node 0 (node 12).

When the Probe packets from source node 4 (destination node 13) as well as node 12 (0), are received at node 0 (12), the node 0 (12) will correlate them on the basis of PathId. With the information in the Route field, node 0 (12) will find the common nodes between working path and the protection path of the *p*-cycle i.e. 4, 6 and 5 (11). Then it will find that the length of the loop backs for 4, 6, and 8 (11) are 7, 8, and 6 (2) respectively. The node 0 (12) will now send Switch packet to 6 (11), the common node with longest loop back path length, containing 5 and 7 (12 and 13) in the FirstNodeId and SecondNodeId field respectively.

After receiving the Switching packet, node 6 (11) will perform the switching action to switch the lightpath direction from node 5 (12) to node 7 (13). This switching will remove the loop backs from the restored path. Then common node 6 (11) will send Release packet to node 5 (12). Node 5 (12) will release the capacity between node 6 and 5 (11 and 12) and forward the packet to the next downstream (upstream) node 0 (11). This process will be repeated till the packet reaches to 6 (11) via 5, 0, 1, 2, 3, 4, 5 (12) releasing the capacity of the loop back. The restored path length will now be seven hops instead of seventeen hops before RLB (Fig. 6.3 (b)).

7.2 OPTIMUM *P*-CYCLES ALLOCATION TO THE PATHS IN THE FAILED SPAN (OPA)

All the working capacity of each span is protected by the *p*-cycles of the solution set (Fig. 5.2 to Fig. 5.5). Without RLB, any link of the span may be protected by any one of the *p*-cycles in the solution set. If the protection capacity available for a span is more than the working capacity of that span, then there is some choice for the selection of *p*-cycles. The *p*-cycles may be selected to minimize the total capacity used by the restored paths. Among all the *p*-cycles protecting the failed span as on-cycle and the left and right paths of *p*-cycles protecting the span as straddling span, the protection path with least length could be selected first. It should be noted that this selection is independent of the working path.

7.2.1 SCENARIO WITH RLB

The situation is entirely different with RLB. The restored path length after removal of loop backs will depend upon allocation of a *p*-cycle to a particular path. This is illustrated in Fig. 7.1. There are two working paths – Path A (1, 0, 8, 6, 5) and Path B (1, 0, 12) (Fig. 7.1 (a)) passing through the failed span 1, 0. There are two *p*-cycles (found with SCO model) to protect 1, 0 as straddling span. These two *p*-cycles provide four protection paths, left path 1 (LP1- 1, 9, 12, 0) and right path 1 (RP1 –1, 2, 10, 3, 4, 5, 6, 7, 8, 11, 0) provided by *p*-cycle 1 (1, 2, 10, 3, 4, 5, 6, 7, 8, 11, 0, 12, 9, 1) and left path 2 (LP2 –1, 9, 12, 10, 11, 0) and right path 2 (RP2- 0, 8, 7, 6, 5, 4, 3, 2, 1) provided by *p*-cycle 2 (1, 9, 12, 10, 11, 0, 8, 7, 6, 5, 4, 3, 2, 1) (Fig. 7.1(a)). Let the Path A be protected by LP2, and Path B be protected by RP1. The restored paths with RLB will be 1, 9, 12, 10, 11, 0, 8, 6, 5 and 1, 2, 10, 3, 4, 5, 6, 7, 8, 11, 0, 12 for Path A and Path B respectively (Fig. 7.1 (b)). In this case the total restored path length is 19 (8 + 11). Now, let the Path A be protected by RP2 and Path B protected by LP1. The restored paths with RLB are 1, 2, 3, 4, 5 and 1, 9, 12 of Path A and Path B respectively (Fig. 7.1 (b)). The total restored path length is now 6 (4 + 2).

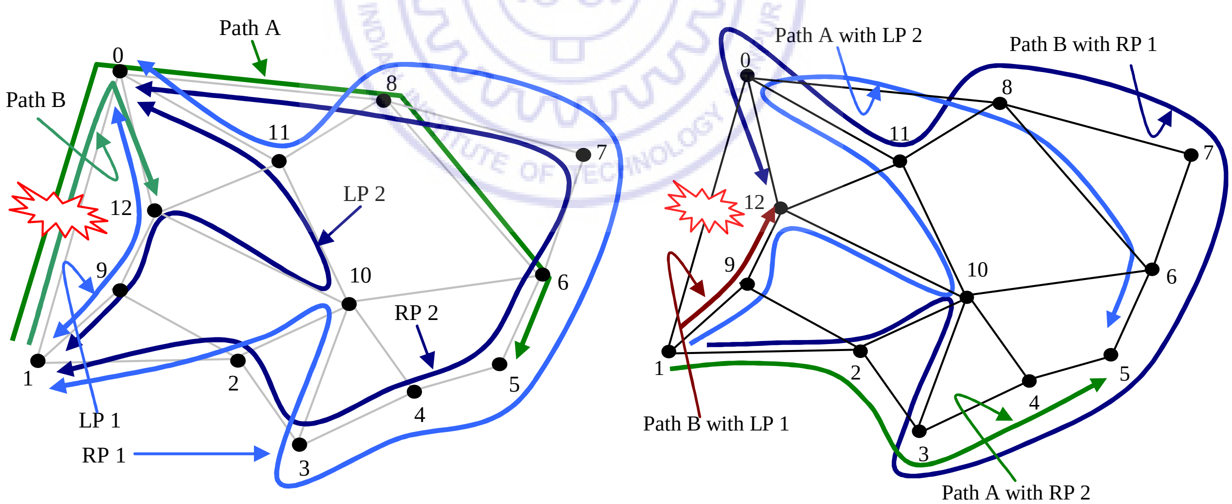


Figure 7-1 **Importance of allocation of *p*-cycles to the working paths, (a) Working paths –Path A and Path B, LP1, RP1, LP2 and RP2 paths of the two *p*-cycles respectively, (b) two of the options for allocation of *p*-cycle paths to the working paths after failure of span 0-1**

This example makes it clear that the restored path lengths depend upon the allocation of the *p*-cycles to the working paths. The straight forward problem of selection of *p*-cycle without RLB is now a complex assignment problem.

7.2.2 PROBLEM FORMULATION

The restored path lengths with RLB of the two paths, Path A and Path B with LP1, RP1, LP2, and RP2 can be represented in the matrix form as shown below

	LP1	RP1	LP2	RP2
Path A	[6,	5,	8,	4]
Path B	[2,	11,	2,	9]

In the above example two out of four *p*-cycle segments are allocated to the two paths, Path A and Path B. This allocation can be done in 12 ways, and one of them is to be selected in such a way that the total restored path lengths with RLB will be minimized. If the number of total paths and the number of total *p*-cycle paths for the failed span are equal then this is minimum-cost (or maximum-weight) maximum cardinality matching on a bipartite graph. It has the complexity of n! combinations (n is the dimension of the square matrix) with brute-force approach. However, the problem can be solved with Hungarian algorithm with the complexity of $O(N^3)$ [147]. The extension of the Hungarian algorithm for rectangular matrices [148] has been used for optimum *p*-cycle allocation (OPA) in the present work[13]. The input matrix element $C_{i,j}$ for the Hungarian algorithm will be given by $C_{i,j} = L_{FR}$ when the i^{th} path is protected by the j^{th} *p*-cycle.

[13] The search of Hungarian algorithm and the Java codes for its implementation have been carried out jointly with Mr. Srinivas during his M. Tech dissertation [149].

The OPA based *p*-cycle assignment to different paths through the failed span can be computed in advance at the incident node of each span as the nodes have complete topology, working path and *p*-cycle information. It should be noted that the *p*-cycle is allocated to a path for protection of one of its link which is passing through the failed span. It is not necessary that the same *p*-cycle is assigned to all the links which are through different spans, of the path. In other spans, different *p*-cycles may be assigned to protect the other links of the same path.

7.3 PERFORMANCE EVALUATION OF RLBOPA

In this chapter for all the test cases of the previous chapter, the *p*-cycles have been allocated as per OPA and then calculations have been performed without RLB (WRLBOPA) and with RLB (RLBOPA) to find the effectiveness of OPA. We shall see later that the performance of WRLB and WRLBOPA is almost same; hence, we have laid emphasis on results with RLBOPA. We have evaluated the performance of RLBOPA in the following sections with the same test scenarios and conditions as were used in previous chapter to evaluate the performance of RLB.

7.3.1 RLBOPA WITH DCPC, SCO AND H-L MODEL

The results of RLBOPA with SCO, H-L and DCPC model are given in Tables 7.1 to 7.12 and Fig. 7.2 to Fig. 7.5. In case of SCO for Net1, the maximum percentage reduction and absolute reduction in the restored path lengths has been increased to 75% and 560 with RLBOPA from 53% and 440 with RLB, respectively (compare Table 6.1 and Table 7.1). Almost the similar changes are there for all other networks and with H-L and DCPC models also. Even for Net4, the maximum percentage reduction in the restored path lengths has increased to 58% with SCO model (Table 7.10), and 67% with H-L model (Table 7.11), making RLBOPA more effective.

In Tables 7.1 to 7.12, the ‘Grey’ spans are the ones for which, there is no reduction in the total restored path lengths for a span. The ‘blue’ spans are the spans showing maximum absolute reduction. The ‘green’ spans corresponds the one’s having maximum percentage reduction in restored path lengths. Further, important fact is the reduction in the ‘grey’ spans in Tables 7.1 to 7.12 as compared to Tables 6.1 to 6.12.It means for the spans which are no more ‘grey’, earlier there were no loop backs, but now there are. However, the restored path lengths, for these spans with RLBOPA (Tables 7.1 to 7.12), are smaller and in some cases equal to the restored path lengths achieved with RLB (Tables 6.1-6.12). At the same time, there are a few new grey spans in Tables 7.1 to 7.12 which were not there earlier. It means that a few grey spans are added due to OPA, but they have smaller restored path lengths. This strengthens the argument that with *p*-cycle protection, to get minimum restored path lengths, the *p*-cycles should be allocated with OPA to get the minimum restored path lengths after removal of loop backs.

Table 7-1 Results of RLBOPA for Net1 with SCO Model

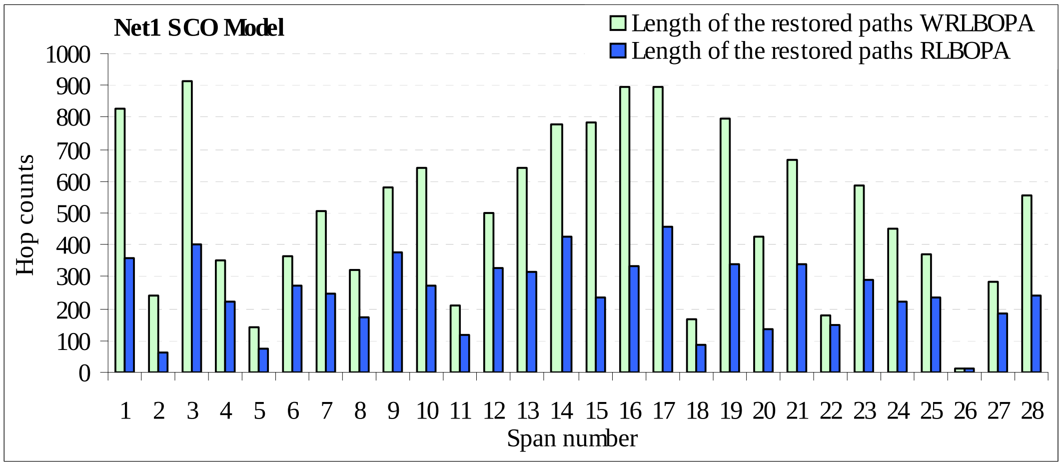
Net1 (Total spare capacity Tsp=754)							
RLBOPA with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	828	358	470	56.76
2	0, 3	18	52	238	60	178	74.79
3	0, 9	68	262	912	402	510	55.92
4	1, 2	22	76	354	222	132	37.29
5	2, 3	16	52	144	76	68	47.22
6	2, 4	22	64	364	270	94	25.82
7	3, 5	30	104	508	244	264	51.97
8	4, 5	30	104	322	174	148	45.96
9	4, 6	32	106	582	374	208	35.74
10	5, 8	48	172	644	272	372	57.76
11	5, 9	24	78	208	118	90	43.27
12	6, 7	28	90	498	326	172	34.54
13	7, 8	56	194	644	314	330	51.24
14	7, 11	44	158	780	426	354	45.38
15	8, 9	54	194	782	234	548	70.08
16	8, 10	66	246	896	336	560	62.50
17	9, 18	70	248	898	458	440	49.00
18	10, 11	20	54	168	86	82	48.81
19	10, 14	64	236	798	340	458	57.39
20	10, 18	26	72	428	134	294	68.69
21	11, 12	36	128	664	340	324	48.80
22	12, 13	12	30	178	146	32	17.98
23	13, 14	32	116	584	290	294	50.34
24	14, 15	24	74	448	222	226	50.45
25	15, 16	20	66	372	236	136	36.56
26	16, 17	4	6	10	10	0	0.00
27	16, 18	40	144	286	186	100	34.97
28	17, 18	32	108	554	238	316	57.04

Table 7-2 Results of RLBOPA for Net1 with H-L Model

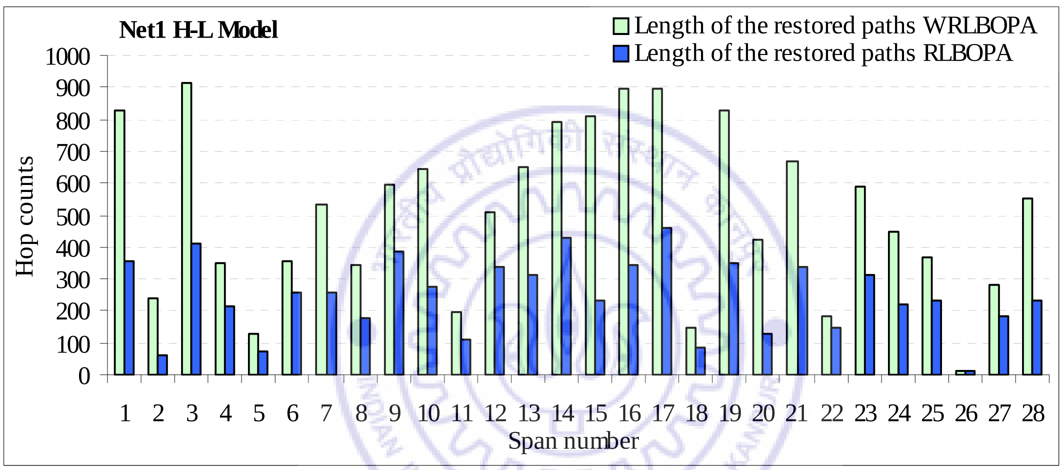
Net1 (Total spare capacity Tsp=754)							
RLBOPA with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	828	358	470	56.76
2	0, 3	18	52	238	60	178	74.79
3	0, 9	68	262	912	408	504	55.26
4	1, 2	22	76	348	216	132	37.93
5	2, 3	16	52	128	76	52	40.63
6	2, 4	22	64	356	258	98	27.53
7	3, 5	30	104	532	258	274	51.50
8	4, 5	30	104	344	176	168	48.84
9	4, 6	32	106	594	386	208	35.02
10	5, 8	48	172	644	276	368	57.14
11	5, 9	24	78	198	112	86	43.43
12	6, 7	28	90	510	338	172	33.73
13	7, 8	56	194	650	312	338	52.00
14	7, 11	44	158	794	432	362	45.59
15	8, 9	54	194	808	234	574	71.04
16	8, 10	66	246	896	346	550	61.38
17	9, 18	70	248	898	458	440	49.00
18	10, 11	20	54	146	86	60	41.10
19	10, 14	64	236	828	350	478	57.73
20	10, 18	26	72	422	128	294	69.67
21	11, 12	36	128	668	336	332	49.70
22	12, 13	12	30	184	148	36	19.57
23	13, 14	32	116	588	312	276	46.94
24	14, 15	24	74	446	220	226	50.67
25	15, 16	20	66	370	234	136	36.76
26	16, 17	4	6	10	10	0	0.00
27	16, 18	40	144	284	184	100	35.21
28	17, 18	32	108	552	236	316	57.25

Table 7-3 Results of RLBOPA for Net1 with DCPC Model

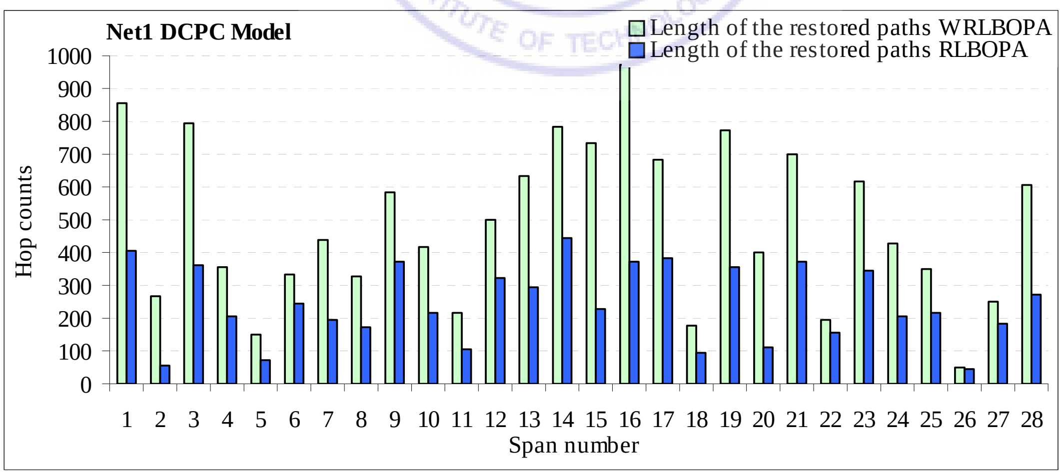
Net1 (Total spare capacity Tsp=922)							
RLBOPA with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	46	178	856	404	452	52.80
2	0, 3	18	52	264	56	208	78.79
3	0, 9	68	262	796	362	434	54.52
4	1, 2	22	76	354	204	150	42.37
5	2, 3	16	52	150	72	78	52.00
6	2, 4	22	64	336	244	92	27.38
7	3, 5	30	104	438	192	246	56.16
8	4, 5	30	104	326	172	154	47.24
9	4, 6	32	106	582	370	212	36.43
10	5, 8	48	172	414	218	196	47.34
11	5, 9	24	78	214	104	110	51.40
12	6, 7	28	90	498	322	176	35.34
13	7, 8	56	194	632	294	338	53.48
14	7, 11	44	158	784	442	342	43.62
15	8, 9	54	194	734	230	504	68.66
16	8, 10	66	246	972	374	598	61.52
17	9, 18	70	248	686	386	300	43.73
18	10, 11	20	54	176	92	84	47.73
19	10, 14	64	236	774	356	418	54.01
20	10, 18	26	72	398	112	286	71.86
21	11, 12	36	128	698	372	326	46.70
22	12, 13	12	30	192	156	36	18.75
23	13, 14	32	116	618	346	272	44.01
24	14, 15	24	74	428	204	224	52.34
25	15, 16	20	66	352	216	136	38.64
26	16, 17	4	6	50	46	4	8.00
27	16, 18	40	144	250	182	68	27.20
28	17, 18	32	108	608	272	336	55.26



(a)



(b)



(c)

Figure 7-2 Total length of the paths of a span with RLBOPA and WRLBOPA for Net1 with (a) SCO model, (b) H-L model and (c) DCPC method

Table 7-4 Results of RLBOPA for Net2 with SCO Model

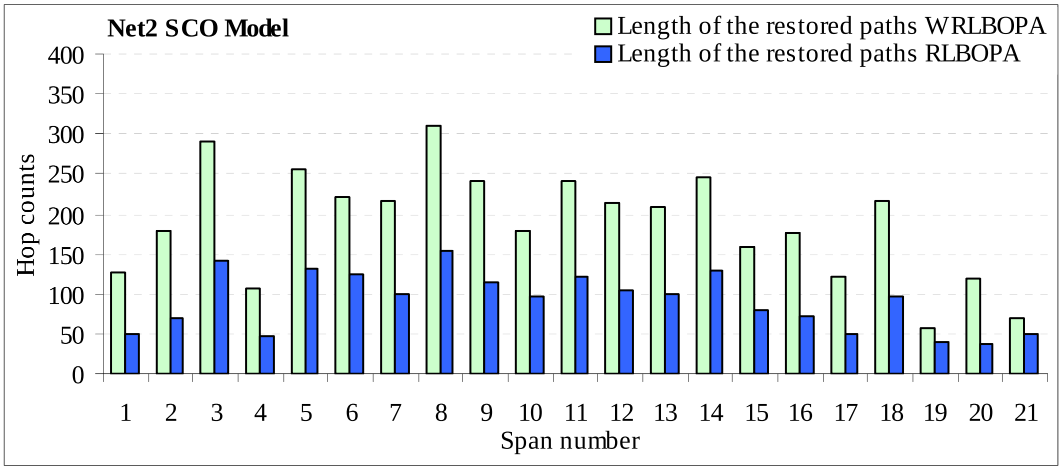
Net2 (Total spare capacity Tsp=286**)**							
RLBOPA with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	126	50	76	60.32
2	0, 2	16	40	180	70	110	61.11
3	0, 7	26	66	290	142	148	51.03
4	1, 2	12	28	108	46	62	57.41
5	1, 3	22	54	256	132	124	48.44
6	2, 5	26	64	222	124	98	44.14
7	3, 4	24	60	216	100	116	53.70
8	3, 9	28	72	310	154	156	50.32
9	4, 5	24	58	242	114	128	52.89
10	4, 6	14	32	180	98	82	45.56
11	5, 8	20	48	242	122	120	49.59
12	5, 11	24	58	214	104	110	51.40
13	6, 7	16	38	208	100	108	51.92
14	7, 10	28	70	246	130	116	47.15
15	8, 10	14	30	158	80	78	49.37
16	9, 12	20	48	176	72	104	59.09
17	9, 13	10	22	122	50	72	59.02
18	10, 12	22	54	216	98	118	54.63
19	10, 13	10	22	56	40	16	28.57
20	11, 12	12	26	120	38	82	68.33
21	11, 13	6	12	70	50	20	28.57

Table 7-5 Results of RLBOPA for Net2 with H-L Model

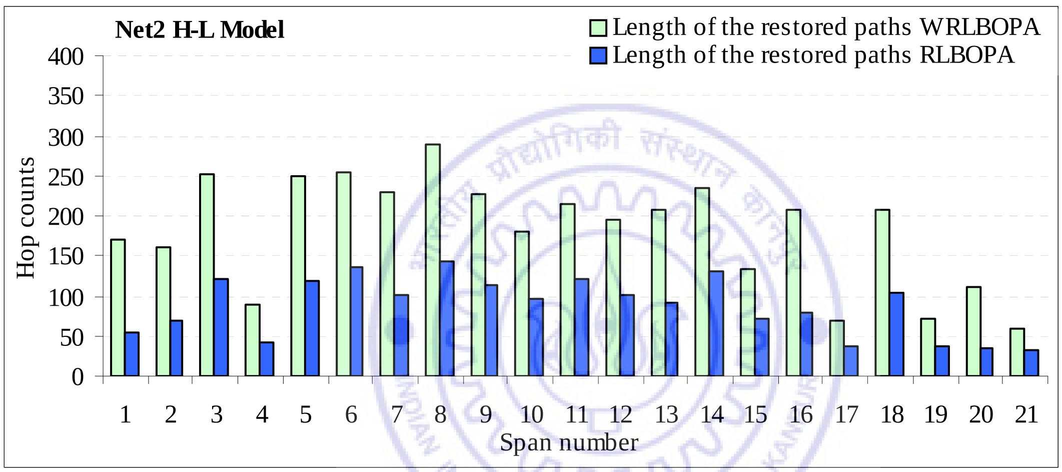
Net2 (Total spare capacity Tsp=286**)**							
RLBOPA with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	170	54	116	68.24
2	0, 2	16	40	160	70	90	56.25
3	0, 7	26	66	252	120	132	52.38
4	1, 2	12	28	90	42	48	53.33
5	1, 3	22	54	250	118	132	52.80
6	2, 5	26	64	254	136	118	46.46
7	3, 4	24	60	230	102	128	55.65
8	3, 9	28	72	290	144	146	50.34
9	4, 5	24	58	228	114	114	50.00
10	4, 6	14	32	180	96	84	46.67
11	5, 8	20	48	216	120	96	44.44
12	5, 11	24	58	194	102	92	47.42
13	6, 7	16	38	208	92	116	55.77
14	7, 10	28	70	234	130	104	44.44
15	8, 10	14	30	134	72	62	46.27
16	9, 12	20	48	208	80	128	61.54
17	9, 13	10	22	68	38	30	44.12
18	10, 12	22	54	208	104	104	50.00
19	10, 13	10	22	72	38	34	47.22
20	11, 12	12	26	110	34	76	69.09
21	11, 13	6	12	60	32	28	46.67

Table 7-6 Results of RLBOPA for Net2 with DCPC Model

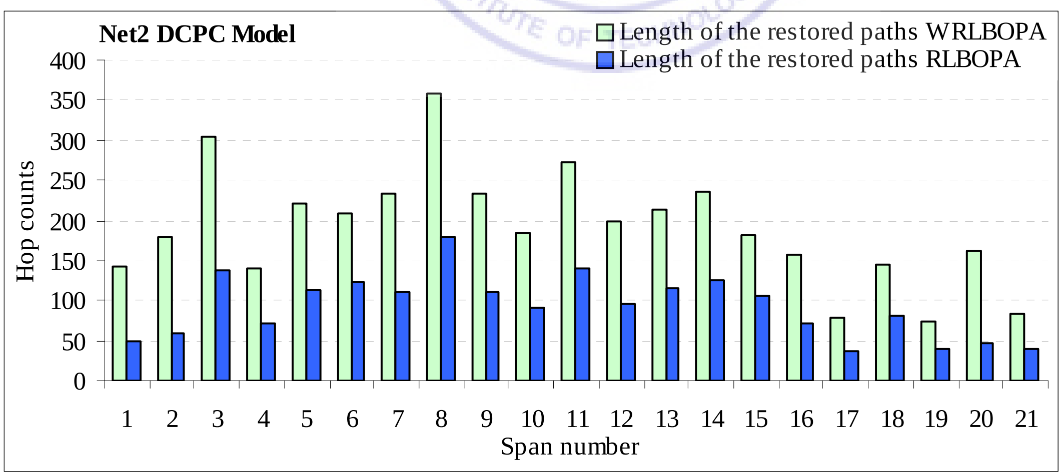
Net2 (Total spare capacity Tsp=362**)**							
RLBOPA with DCPC Model							
S. No.	Span	Working capacity w_i	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	16	40	142	50	92	64.79
2	0, 2	16	40	178	60	118	66.29
3	0, 7	26	66	304	138	166	54.61
4	1, 2	12	28	140	70	70	50.00
5	1, 3	22	54	220	114	106	48.18
6	2, 5	26	64	208	122	86	41.35
7	3, 4	24	60	232	110	122	52.59
8	3, 9	28	72	358	178	180	50.28
9	4, 5	24	58	234	110	124	52.99
10	4, 6	14	32	184	92	92	50.00
11	5, 8	20	48	272	140	132	48.53
12	5, 11	24	58	200	96	104	52.00
13	6, 7	16	38	214	116	98	45.79
14	7, 10	28	70	236	124	112	47.46
15	8, 10	14	30	182	106	76	41.76
16	9, 12	20	48	158	72	86	54.43
17	9, 13	10	22	78	36	42	53.85
18	10, 12	22	54	144	82	62	43.06
19	10, 13	10	22	74	40	34	45.95
20	11, 12	12	26	162	46	116	71.60
21	11, 13	6	12	84	40	44	52.38



(a)



(b)



(c)

Figure 7-3 Total length of the paths of a span with RLBOPA and WRLBOPA for Net2 with (a) SCO model, (b) H-L model, (c) DCPC method

Table 7-7 Results of RLBOPA for Net3 with SCO Model

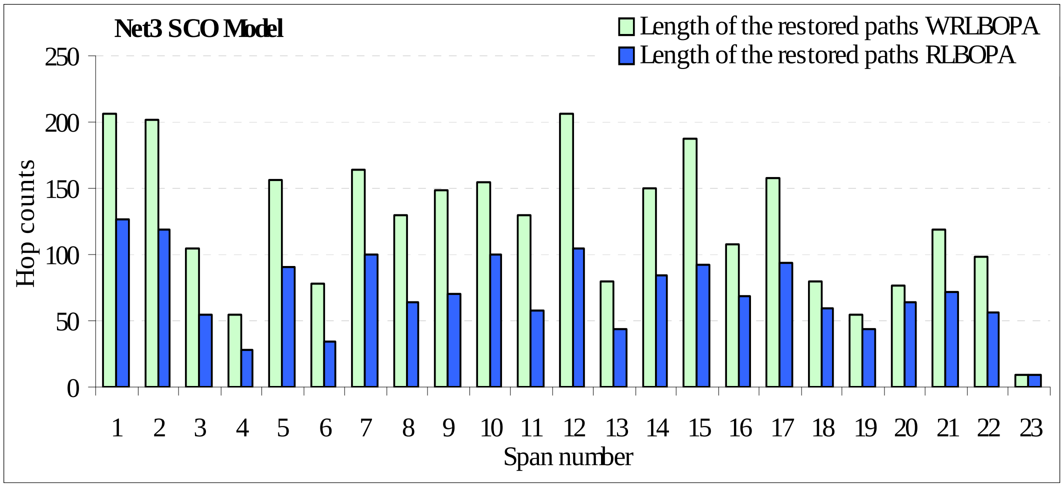
Net3 (Total spare capacity Tsp=194)							
RLBOPA with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	206	126	80	38.83
2	0, 8	22	56	202	118	84	41.58
3	0, 11	8	16	104	54	50	48.08
4	0, 12	6	10	54	28	26	48.15
5	1, 2	14	32	156	90	66	42.31
6	1, 9	6	12	78	34	44	56.41
7	2, 3	18	46	164	100	64	39.02
8	2, 9	16	42	130	64	66	50.77
9	2, 10	16	38	148	70	78	52.70
10	3, 4	14	36	154	100	54	35.06
11	3, 10	12	26	130	58	72	55.38
12	4, 5	20	52	206	104	102	49.51
13	4, 10	14	32	80	44	36	45.00
14	5, 6	16	40	150	84	66	44.00
15	6, 7	16	42	188	92	96	51.06
16	6, 8	20	50	108	68	40	37.04
17	6, 10	24	60	158	94	64	40.51
18	7, 8	8	16	80	60	20	25.00
19	8, 11	6	10	54	44	10	18.52
20	9, 12	6	10	76	64	12	15.79
21	10, 11	14	30	118	72	46	38.98
22	10, 12	12	26	98	56	42	42.86
23	11, 12	4	6	10	10	0	0.00

Table 7-8 Results of RLBOPA for Net3 with H-L Model

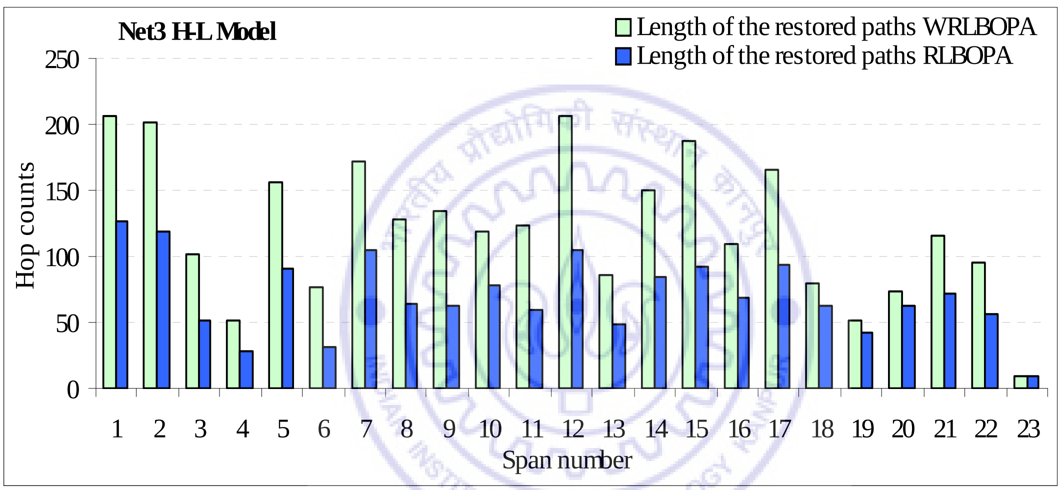
Net3 (Total spare capacity Tsp=194)							
RLBOPA with H-L Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	206	126	80	38.83
2	0, 8	22	56	202	118	84	41.58
3	0, 11	8	16	102	52	50	49.02
4	0, 12	6	10	52	28	24	46.15
5	1, 2	14	32	156	90	66	42.31
6	1, 9	6	12	76	32	44	57.89
7	2, 3	18	46	172	104	68	39.53
8	2, 9	16	42	128	64	64	50.00
9	2, 10	16	38	134	62	72	53.73
10	3, 4	14	36	118	78	40	33.90
11	3, 10	12	26	124	60	64	51.61
12	4, 5	20	52	206	104	102	49.51
13	4, 10	14	32	86	48	38	44.19
14	5, 6	16	40	150	84	66	44.00
15	6, 7	16	42	188	92	96	51.06
16	6, 8	20	50	110	68	42	38.18
17	6, 10	24	60	166	94	72	43.37
18	7, 8	8	16	80	62	18	22.50
19	8, 11	6	10	52	42	10	19.23
20	9, 12	6	10	74	62	12	16.22
21	10, 11	14	30	116	72	44	37.93
22	10, 12	12	26	96	56	40	41.67
23	11, 12	4	6	10	10	0	0.00

Table 7-9 Results of RLBOPA for Net3 with DCPC Model

Net3 (Total spare capacity Tsp=250**)**							
RLBOPA with DCPC Model							
S. No.	Span	Working capacity w_i	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	24	60	198	116	82	41.41
2	0, 8	22	56	194	110	84	43.30
3	0, 11	8	16	104	56	48	46.15
4	0, 12	6	10	54	28	26	48.15
5	1, 2	14	32	136	78	58	42.65
6	1, 9	6	12	78	34	44	56.41
7	2, 3	18	46	116	76	40	34.48
8	2, 9	16	42	130	64	66	50.77
9	2, 10	16	38	142	62	80	56.34
10	3, 4	14	36	128	78	50	39.06
11	3, 10	12	26	130	52	78	60.00
12	4, 5	20	52	234	132	102	43.59
13	4, 10	14	32	66	46	20	30.30
14	5, 6	16	40	178	112	66	37.08
15	6, 7	16	42	174	84	90	51.72
16	6, 8	20	50	104	66	38	36.54
17	6, 10	24	60	174	96	78	44.83
18	7, 8	8	16	72	52	20	27.78
19	8, 11	6	10	54	44	10	18.52
20	9, 12	6	10	76	64	12	15.79
21	10, 11	14	30	118	72	46	38.98
22	10, 12	12	26	106	56	50	47.17
23	11, 12	4	6	10	10	0	0.00



(a)



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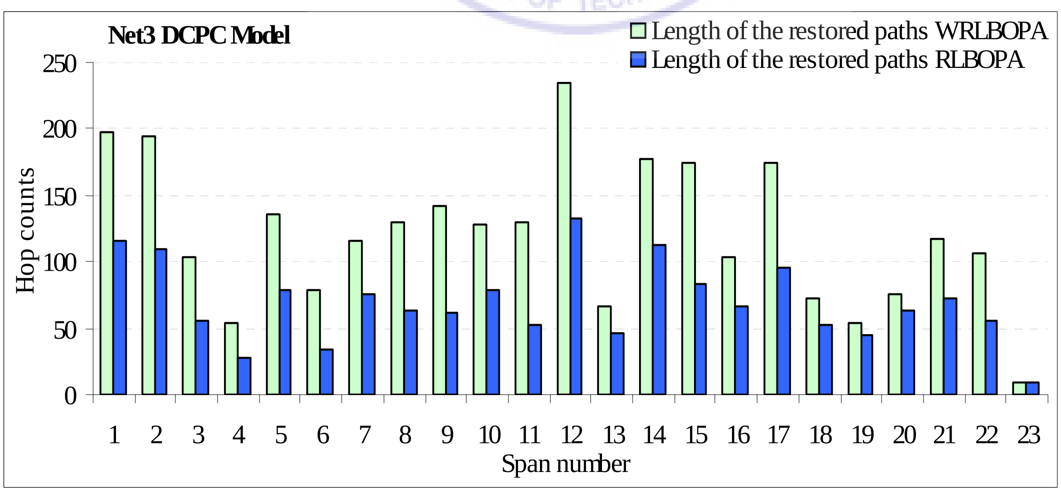


(c)

Figure 7-4 Total length of the paths of a span with RLBOPA and WRLBOPA for Net3 with (a) SCO model, (b) H-L model, (c) DCPC method

Table 7-10 Results of RLBOPA for Net4 with SCO Model

Net4 (Total spare capacity Tsp=70**)**							
RLBOPA with SCO Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	48	38	44.19
2	0, 2	14	30	84	50	34	40.48
3	0, 3	6	10	36	24	12	33.33
4	0, 4	4	6	34	28	6	17.65
5	1, 3	6	10	52	22	30	57.69
6	1, 7	10	22	76	38	38	50.00
7	2, 4	6	10	54	38	16	29.63
8	2, 6	6	10	30	20	10	33.33
9	2, 8	8	16	70	48	22	31.43
10	3, 4	4	6	10	10	0	0.00
11	3, 5	8	14	46	32	14	30.43
12	3, 6	8	14	46	30	16	34.78
13	3, 7	6	10	28	14	14	50.00
14	4, 5	6	10	34	24	10	29.41
15	4, 6	2	2	8	8	0	0.00
16	5, 6	4	6	38	32	6	15.79
17	5, 7	2	2	18	18	0	0.00
18	5, 9	6	10	28	16	12	42.86
19	6, 8	6	10	28	18	10	35.71
20	6, 9	4	6	38	22	16	42.11
21	7, 9	8	16	46	30	16	34.78
22	8, 9	4	6	28	24	4	14.29

Table 7-11 Results of RLBOPA for Net4 with H-L Model

Net4 (Total spare capacity Tsp=70)							
RLBOPA with H-L Model							
S. No.	Span	Working capacity w_i	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	44	42	48.84
2	0, 2	14	30	84	46	38	45.24
3	0, 3	6	10	36	22	14	38.89
4	0, 4	4	6	32	26	6	18.75
5	1, 3	6	10	50	24	26	52.00
6	1, 7	10	22	76	40	36	47.37
7	2, 4	6	10	52	36	16	30.77
8	2, 6	6	10	38	26	12	31.58
9	2, 8	8	16	58	38	20	34.48
10	3, 4	4	6	10	10	0	0.00
11	3, 5	8	14	42	28	14	33.33
12	3, 6	8	14	38	24	14	36.84
13	3, 7	6	10	24	14	10	41.67
14	4, 5	6	10	28	18	10	35.71
15	4, 6	2	2	4	4	0	0.00
16	5, 6	4	6	34	28	6	17.65
17	5, 7	2	2	14	14	0	0.00
18	5, 9	6	10	26	16	10	38.46
19	6, 8	6	10	38	26	12	31.58
20	6, 9	4	6	24	8	16	66.67
21	7, 9	8	16	58	36	22	37.93
22	8, 9	4	6	34	26	8	23.53

Table 7-12 Results of RLBOPA for Net4 with DCPC Model

Net4 (Total spare capacity Tsp=70)							
RLBOPA with DCPC Model							
S. No.	Span	Working capacity w_j	Length of working paths	Length of the restored paths WRLBOPA	Length of the restored paths RLBOPA	Reduction in Length	Percent reduction in Length
1	0, 1	14	32	86	48	38	44.19
2	0, 2	14	30	84	50	34	40.48
3	0, 3	6	10	38	24	14	36.84
4	0, 4	4	6	34	28	6	17.65
5	1, 3	6	10	52	22	30	57.69
6	1, 7	10	22	76	38	38	50.00
7	2, 4	6	10	54	38	16	29.63
8	2, 6	6	10	30	20	10	33.33
9	2, 8	8	16	70	48	22	31.43
10	3, 4	4	6	10	10	0	0.00
11	3, 5	8	14	46	32	14	30.43
12	3, 6	8	14	46	30	16	34.78
13	3, 7	6	10	28	14	14	50.00
14	4, 5	6	10	34	24	10	29.41
15	4, 6	2	2	8	8	0	0.00
16	5, 6	4	6	38	32	6	15.79
17	5, 7	2	2	18	18	0	0.00
18	5, 9	6	10	28	16	12	42.86
19	6, 8	6	10	28	18	10	35.71
20	6, 9	4	6	38	22	16	42.11
21	7, 9	8	16	46	30	16	34.78
22	8, 9	4	6	32	24	8	25.00

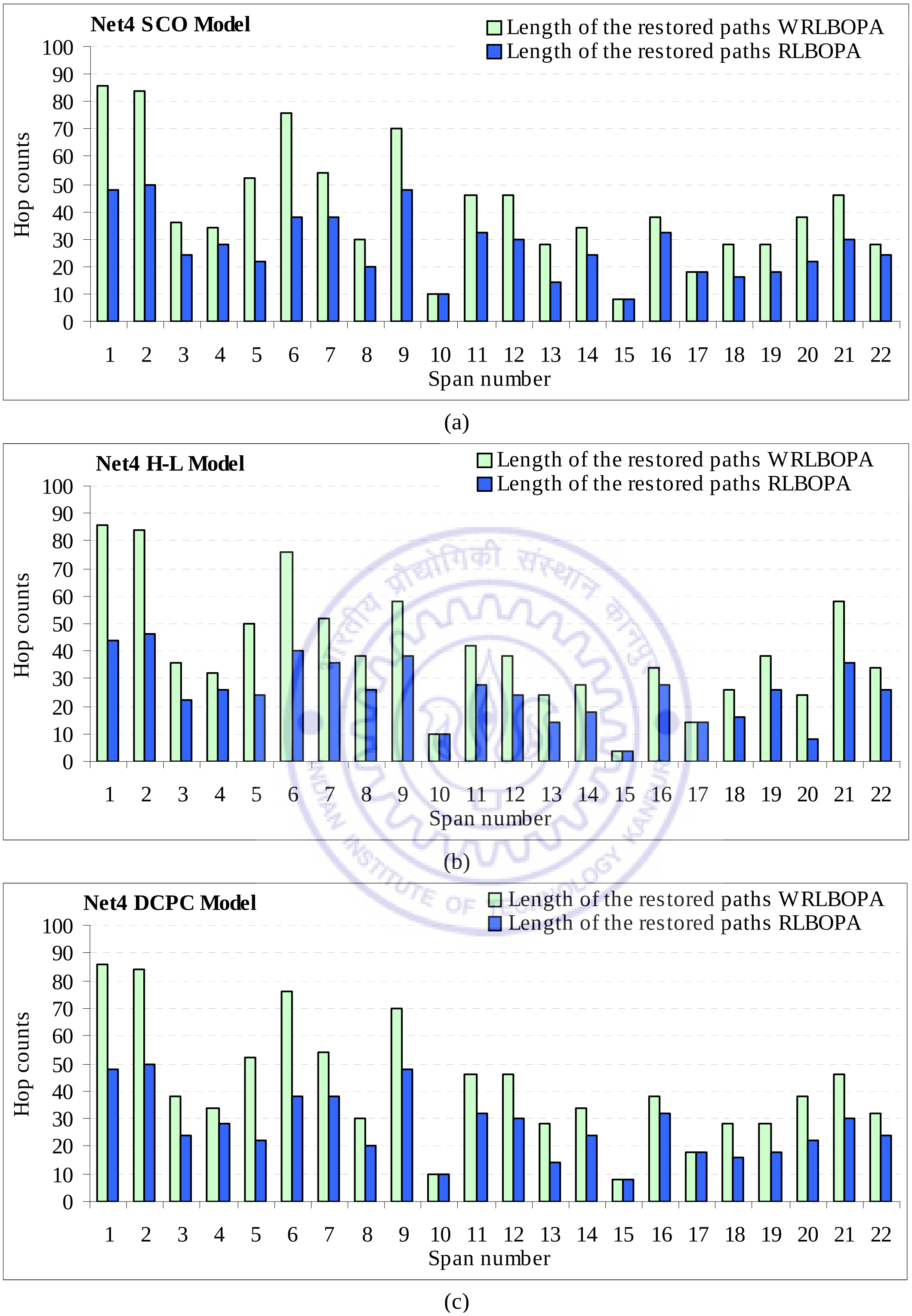


Figure 7-5 Total length of the paths of a span with RLBOPA and WRLBOPA for Net4 with (a) SCO model, (b) H-L model, (c) DCPC method

The difference in the restored path lengths with WRLBOPA and with RLBOPA has been shown in Fig. 7.2 to Fig. 7.5. The length of the restored paths with RLBOPA is now much shorter as compared to the RLB (Fig. 6.6 to Fig. 6.9). One can make another observation also that distribution of path lengths is similar with RLBOPA and WRLBOPA for all the methods of *p*-cycle formation for a test network. The above observation is also true for all other test networks (Fig. 7.2 to Fig. 7.5).

The L_{WRLB} and L_{RLB} values (when OPA has also been used with RLB and WRLB both) for all the test networks are shown in Table 8.13 and plotted in Fig. 7.6. The context will always make it clear whether L_{WRLB} and L_{RLB} values are with OPA or without OPA. With RLBOPA, the restored path lengths L_{RLB}, for a network with all the models, is of the same order and the reduction in the restored path lengths is also more or less same. It can now be concluded that performance of RLBOPA is independent of the method of formation of *p*-cycles. Thus for a particular network, the amount of reduction in the restored path lengths is almost constant and quite significant.

Table 7-13 Effect of RLBOPA with SCO, H-L and DCPC methods

Models	Average Length of *p*-cycles	With OPA			Percent Reduction
		L_{WRLB}	L_{RLB}	L_{WRLB} - L_{RLB}	
Net1					
SCO	15.08	14.32	7.00	7.32	51.09
H-L	15.08	14.41	7.06	7.35	50.99
DCPC	15.90	13.80	6.91	6.89	49.93
Net2					
SCO	11.92	10.15	4.91	5.24	51.64
H-L	11.00	9.78	4.71	5.07	51.83
DCPC	12.07	10.27	4.98	5.29	51.50
Net3					
SCO	9.70	9.03	5.17	3.85	42.71
H-L	9.70	8.87	5.09	3.78	42.65
DCPC	10.42	8.78	5.03	3.76	42.80
Net4					
SCO	8.75	6.46	4.18	2.28	35.29
H-L	8.75	6.24	3.90	2.34	37.47
DCPC	8.75	6.51	4.18	2.32	35.71

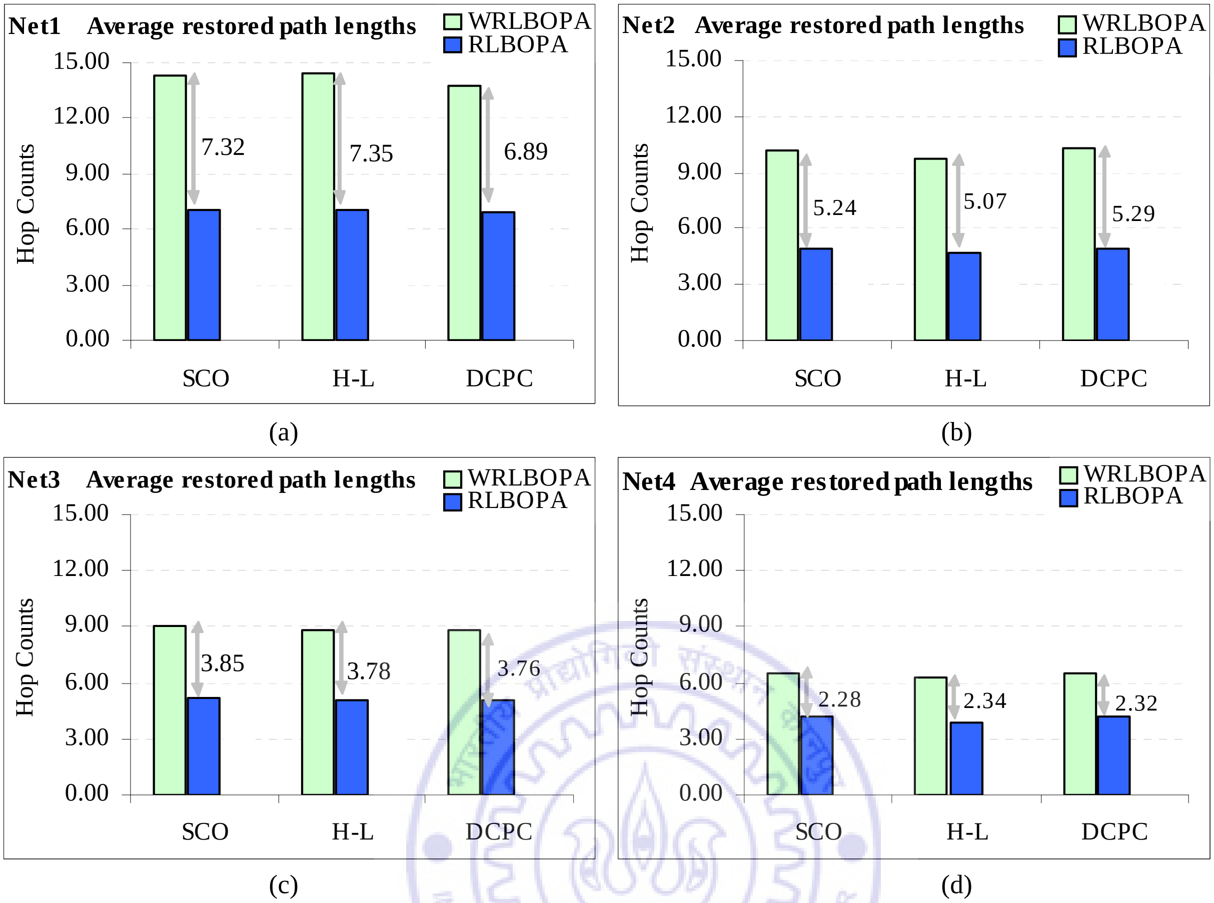
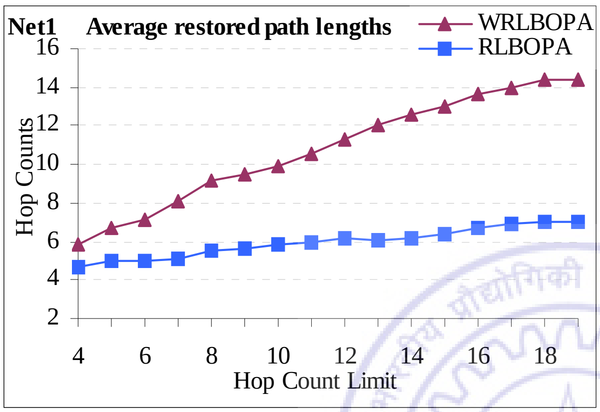


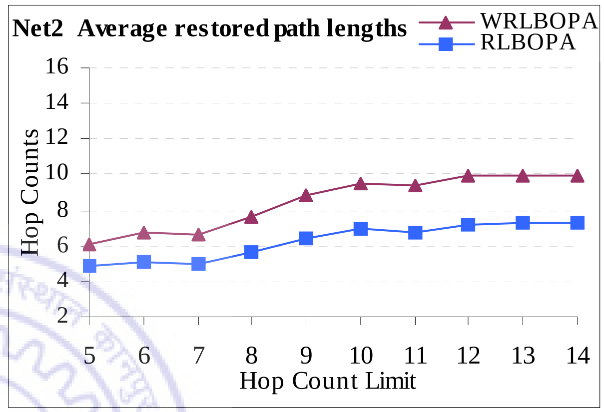
Figure 7-6 **The average restored path lengths (L_{WRLB} and L_{RLB}) with RLBOPA and WRLBOPA for (a) Net1, (b) Net2, (c) Net3 and (d) Net4, with various *p*-cycle formation models**

7.3.2 RLBOPA WITH H-L MODEL

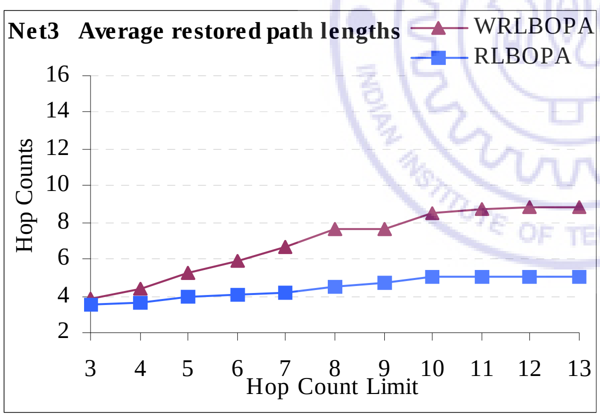
The results for hop count limited model are shown in Fig. 7.7. The curves with and without OPA (Fig. 6.11 and Fig. 7.7) are similar, however with OPA, the difference between L_{WRLB} and L_{RLB} is now more. For smaller values of hop count limit, the restored path lengths are small, and reduction in the restored path length with RLBOPA is also very small. This is due to the same fact that with smaller hop count limits, there is almost no loop backs. However for these cases, the initial spare capacity required for the formation of the set of *p*-cycles is quite large (Fig. 6.12). If smaller *p*-cycles are used, obviously, restored paths will be shorter with less loop backs, but with more initial spare capacity. Whereas, smaller restored path lengths can be obtained with RLBOPA, even with longer *p*-cycles which are obtained while optimizing initial spare capacity. For example, in Net1, if we want to keep the average restored path length to be less than 7, then with WRLBOPA, we need to constraint the hop count limit to 5. While using RLBOPA, no hop count limit is required.



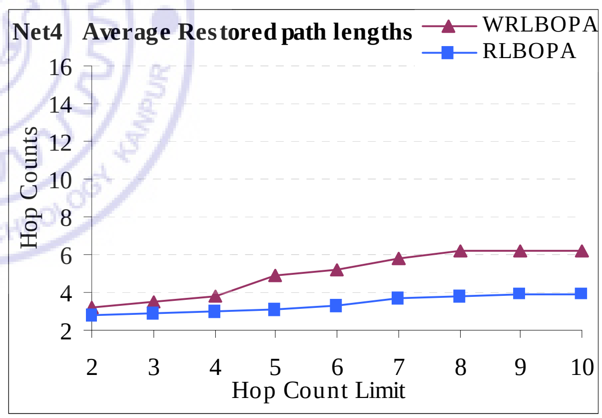
(a)



(b)



(c)



(d)

Figure 7-7 The average restored path lengths (L_{WRLB} and L_{RLB}) with RLBOPA for various hop count limits for (a) Net1, (b) Net2, (c) Net3 and (d) Net4

7.3.3 RLBOPA WITH AVERAGE NODAL DEGREE

The results with OPA for WRLB and RLB with SCO model are shown in Fig. 7.8. We observe the similar trend as observed without OPA, but with smaller values of L_{RLB} for

OPA. The L_{WRLB} values are reducing faster as compared to L_{RLB} values because with higher node degrees there will be more straddling spans and L_{WRLB} values will be smaller, because with straddling spans lengths of *p*-cycle restoration paths will be relatively smaller. The working path lengths will also be smaller with higher node degrees and hence, loop backs will also be less. Therefore, reduction in L_{RLB} is also less with higher node degree.

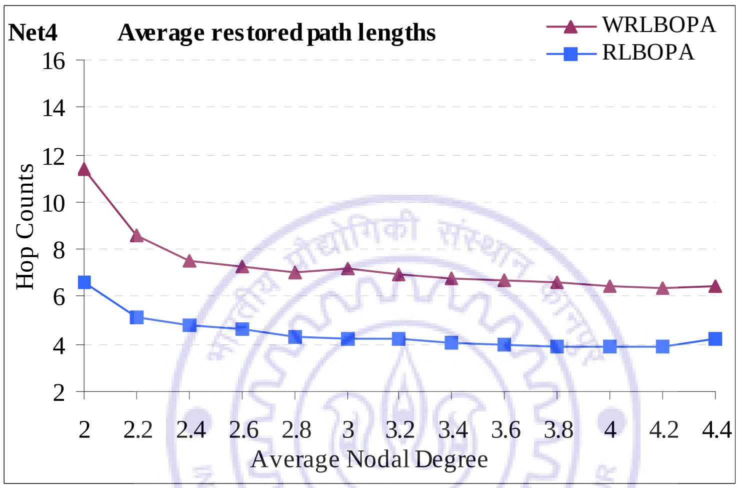
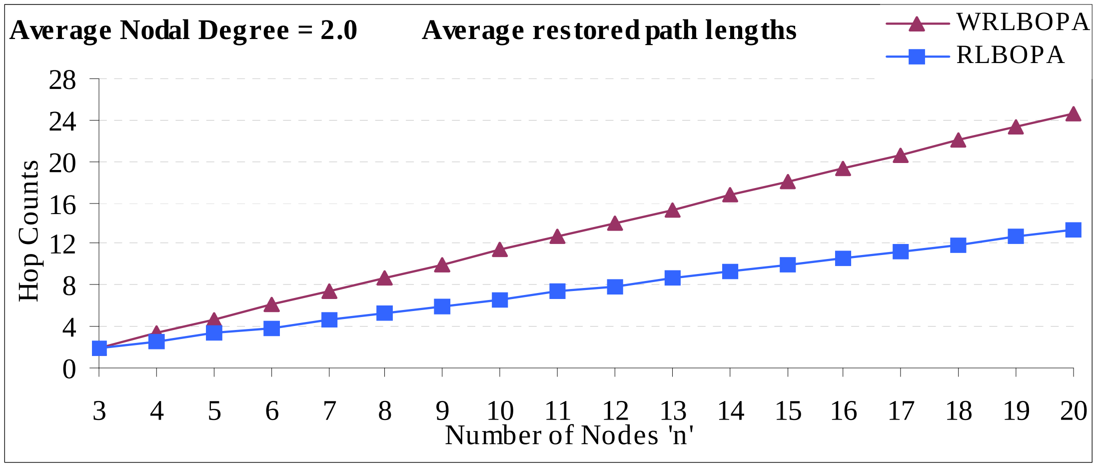


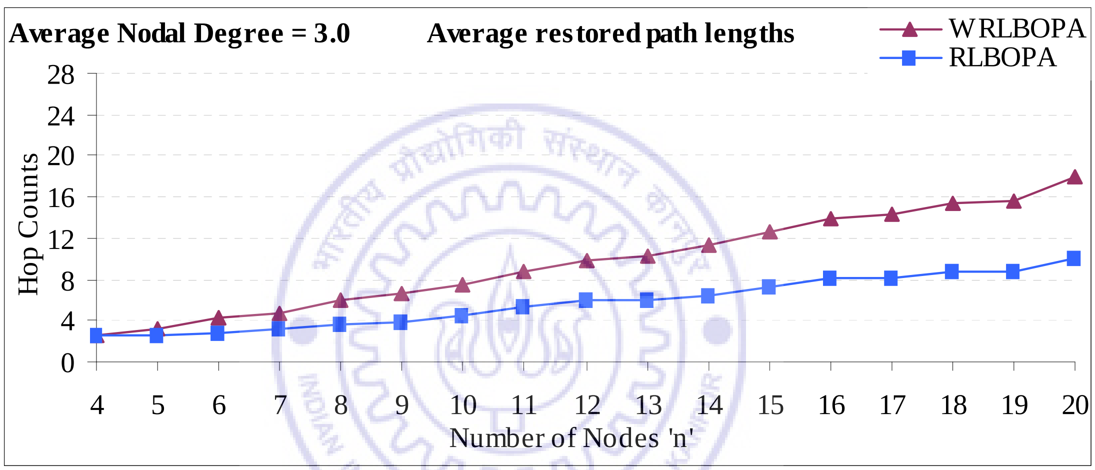
Figure 7-8 **The L_{WRLB} and L_{RLB} values with RLBOPA for Net4 with average nodal degree**

7.3.4 RLBOPA WITH NUMBER OF NODES IN THE NETWORK

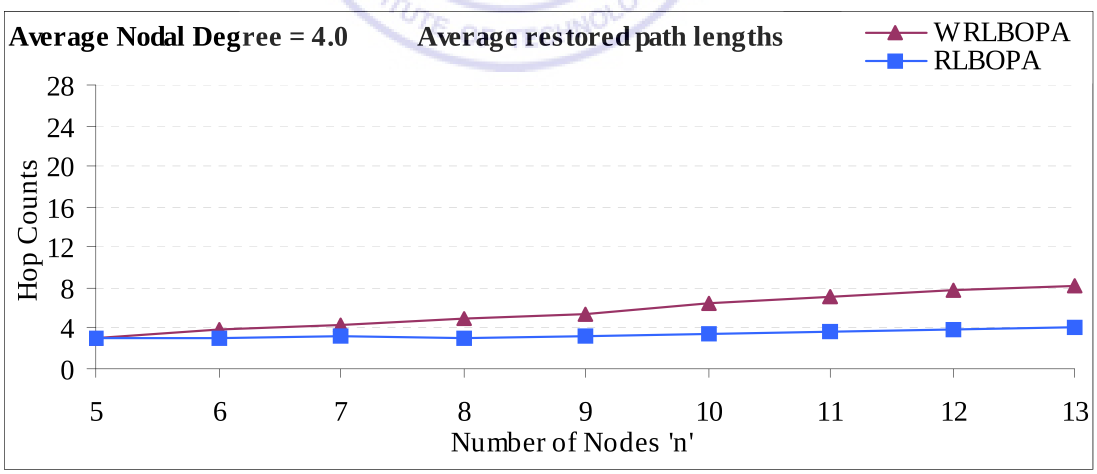
The results for $\overline{d}$ = 2.0, 3.0 and 4.0 are shown in Fig. 7.9 (a), (b), and (c) respectively. These curves are also following the same trend as with RLB, but with smaller values of L_{RLB} for OPA. However, for $\overline{d}$ = 2.0, the curves for RLB and RLBOPA are same, because for this case there is only one *p*-cycle and hence, no choice for assignment of the *p*-cycles to the working paths in OPA. Therefore, there is no change in the amount of reduction in the restored path lengths.



(a)



(b)



(c)

Figure 7-9 **The L_{WRLB} and L_{RLB} values with RLBOPA for (a) $\overline{d}$ = 2.0, (b) $\overline{d}$ = 3.0 and (c) $\overline{d}$ = 4.0**

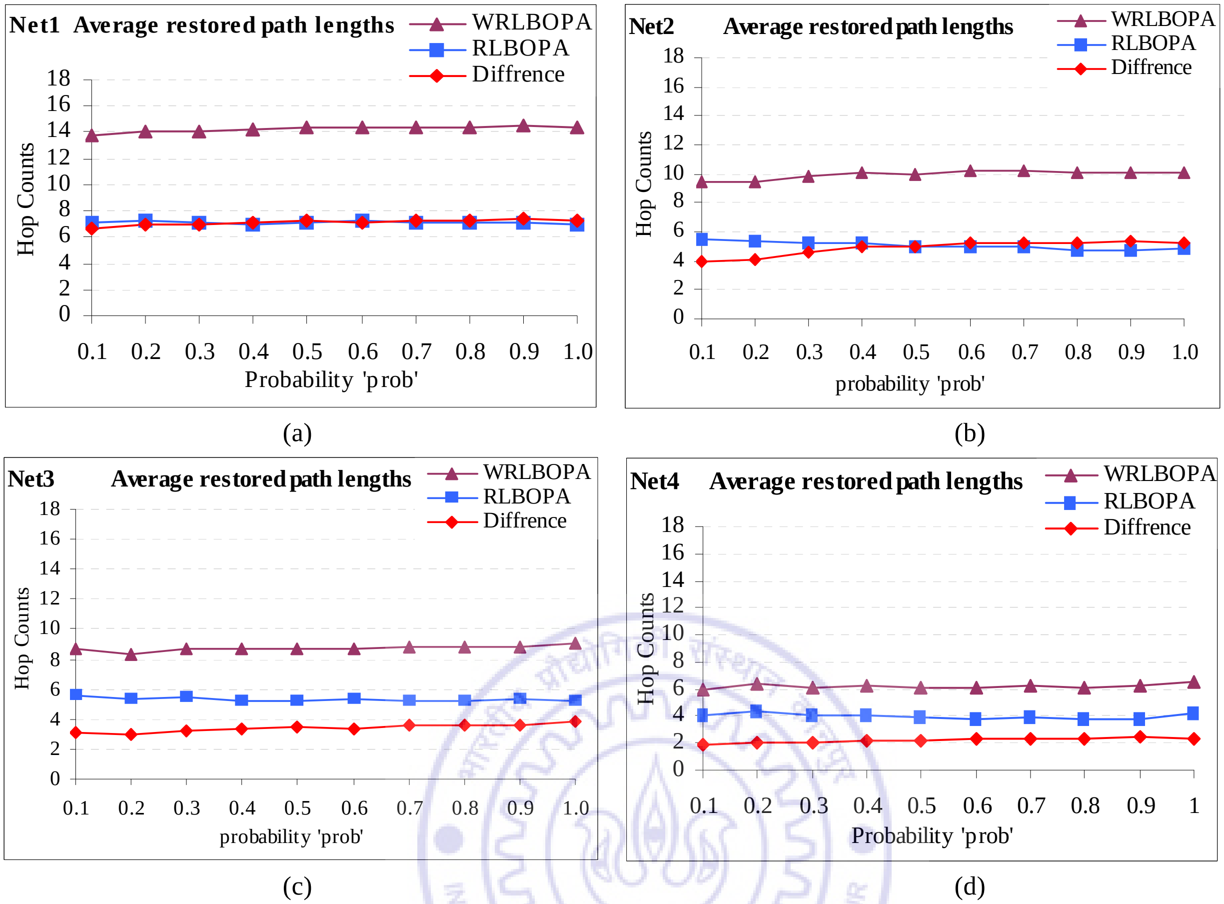


Figure 7-10 The L_{WRLB}, L_{RLB} and L_{WRLB} - L_{RLB} (difference) values with OPA for (a) Net1, (b) Net2, (c) Net3 and (d) Net4 with various traffic distributions

7.3.5 RLBOPA WITH VARIOUS LOADS

The results of RLBOPA with variation in load are shown in Fig. 7.10. It should be noted that in this case the *p*-cycles are formed with SCO model as per the working capacities on the spans for the given load. The difference in L_{WRLB} and L_{RLB} with OPA is again constant as in RLB except for very small loads. The difference in L_{WRLB} and L_{RLB} is slightly small for smaller loads i.e. ‘prob’ values of 0.1 - 0.2 (Fig. 7.10). This is due to the fact that with small traffic in the network, the spare capacity required to provide *p*-cycle protection to the traffic is also small. Usually just one *p*-cycle is sufficient to provide the protection to this small traffic, and hence, no choice for OPA. Thus for smaller load the difference in L_{WRLB} and L_{RLB} is less. However, as the load in the network increases and more than one *p*-cycle are available, the OPA starts performing and the difference in L_{WRLB} and L_{RLB} increases and becomes constant as with RLB (Fig. 6.16). For Net1 and Net2 the curve for difference in L_{WRLB} and L_{RLB}, crosses the curve for L_{RLB}. It means the reduction is more than 50%.

7.3.6 RLBOPA IN CASE OF DUAL FAILURE SURVIVABILITY

The RLBOPA provides significant reduction in the restored path lengths. With RLBOPA, the average reduction in the restored path lengths increases to as much as 50% (Net1 –Table 7.13). Thus on an average, about 50% of the capacity will be released with removal of loop back and OPA. The additional released capacity with RLBOPA can be used for providing protection in the event of second failure. Again, the effect on survivability for dual failures has been observed in the two ways as in section 7.5.7. The procedure is again given below for ready reference.

- ***EFFECT ON RESTORATION OF LINKS DURING SECOND FAILURE***

The effect on the total number of links which can be protected against second failure with RLBOPA and WRLBOPA has been compared. The network is provisioned with initial spare capacity as obtained in the SCO model. Following steps are used for calculating the percentage of links which can be protected against second failure.

Step 1- Failure of any one span is assumed, all the paths passing through that span have been restored with RLBOPA and WRLBOPA.

Step 2- The working capacity of all the remaining spans have been modified to include the capacity used by restored paths of the failed span with RLBOPA and WRLBOPA.

Step 3- The spare capacity is also modified to remove the capacity used for restoration of the paths of the failed span with RLBOPA and WRLBOPA and the capacity which is released from RLBOPA is added to the spare capacity.

Step 4- The DCPC method is used to form the *p*-cycles in the spare capacity, and number of links which can be protected by the formed set of *p*-cycles is counted with RLBOPA and WRLBOPA.

Step 5- Step 1 to step 4 are repeated for each span and then average is taken to find out the percentage of links that can be protected against second failure with RLBOPA and WRLBOPA.

The results are shown in Fig. 7.11. The results (Fig. 7.11) show the improvement in the percentage of links restored with RLBOPA in the event of second failure. For all the networks, the percentage of links which can be protected during second failure is more with RLBOPA, with the same amount of initial spare capacity and the maximum improvement 26.4% is for test network, Net2, i.e. 26.4% more links could be protected in the event of second failure with RLBOPA as compared to WRLBOPA.

- ***REQUIREMENT OF SPARE CAPACITY FOR SECOND FAILURE RESTORABILITY***

In this case, after step 1 and step 2 of the previous case, SCO model is used to find the total amount of spare capacity for 100% dual failure restorability with RLBOPA and WRLBOPA. With this model, we have the values of required spare capacity on each span (after failure of a span) for 100% protection during second failure. The above process is repeated for each span in the network considering it as a failed span and then the maximum capacity value required on every span is taken for 100% dual failure restorability with RLBOPA and WRLBOPA.

The percentage reduction in the amount of initial spare capacity to be provisioned with RLBOPA has also been shown in Fig. 7.11. With RLBOPA for all the test networks the amount of initial capacity to be provisioned for 100% restorability, is smaller. Again the maximum improvement is obtained for Net 2, about 17%. It means, initially 17% less capacity is to be provisioned in the network to provide dual failure survivability.

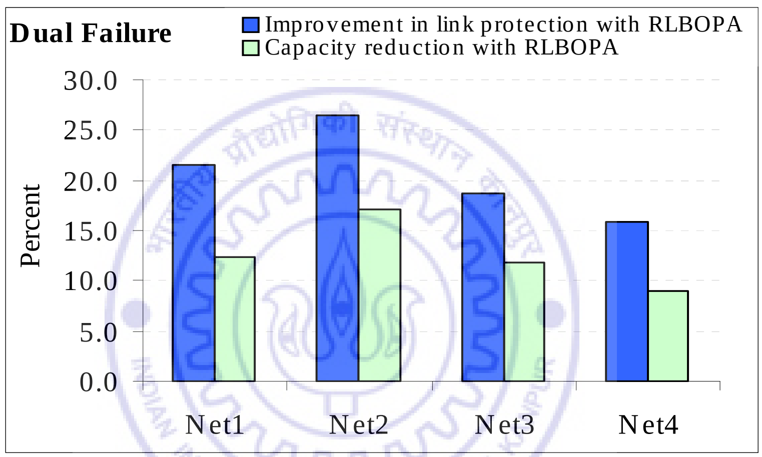


Figure 7-11 Percent improvement in the link protection against second failure and reduction in the spare capacity required for 100% dual failure restorability with RLBOPA over WRLBOPA

7.4 IMPROVEMENTS WITH RLBOPA

The L_{RLB} with RLBOPA is always smaller than L_{RLB} with only RLB. Hence, the reduction in the average restored path lengths or the difference in L_{WRLB} and L_{RLB} with RLBOPA is always more than the difference in L_{WRLB} and L_{RLB} with only RLB. The comparative results for SCO, H-L and DCPC models are shown in Table 7.14. This is also to be noted that the values of L_{WRLB} remains almost the same with WRLB and WRLBOPA.

Thus, the OPA is effective only with RLB and the assignment of p-cycles to the working paths has no visible effects without RLB. For Net1, Net2 and Net4, the improvement in the percent reduction is about 15%. For Net3, the same improvement is there except for H-L model. With H-L model for Net3, even without OPA, the *p*-cycles have been coincidentally assigned to have minimum L_{RLB}, and hence there is no improvement. However, the L_{RLB} value with RLBOPA for H-L model is in agreement with the values in other models.

Table 7-14 Comparison of L_{WRLB}, L_{RLB}, and L_{WRLB} - L_{RLB} without and with OPA for different models

Models	L_{WRLB} (Hop counts)		L_{RLB} (Hop counts)		L_{WRLB} - L_{RLB} (Hop counts)		Percent Reduction	
	Without OPA	With OPA	Without OPA	With OPA	Without OPA	With OPA	Without OPA	With OPA
Net1								
SCO	14.54	14.32	9.38	7.00	5.16	7.32	35.47	51.09
H-L	14.08	14.41	9.08	7.06	5.00	7.35	35.52	50.99
DCPC	16.14	13.80	9.91	6.91	6.23	6.89	38.58	49.93
Net2								
SCO	10.41	10.15	7.08	4.91	3.33	5.24	31.99	51.64
H-L	9.90	9.77	7.30	4.71	2.61	5.06	26.31	51.76
DCPC	11.29	10.27	7.72	4.98	3.56	5.29	31.58	51.50
Net3								
SCO	9.32	8.99	6.63	5.17	2.70	3.82	28.92	42.46
H-L	9.03	8.86	5.17	5.09	3.85	3.77	42.71	42.57
DCPC	9.63	8.78	6.91	5.03	2.72	3.76	28.27	42.80
Net4								
SCO	6.49	6.46	5.04	4.18	1.45	2.28	22.34	35.29
H-L	6.14	6.24	4.90	3.90	1.24	2.34	20.18	37.47
DCPC	6.73	6.51	5.07	4.18	1.66	2.32	24.69	35.71

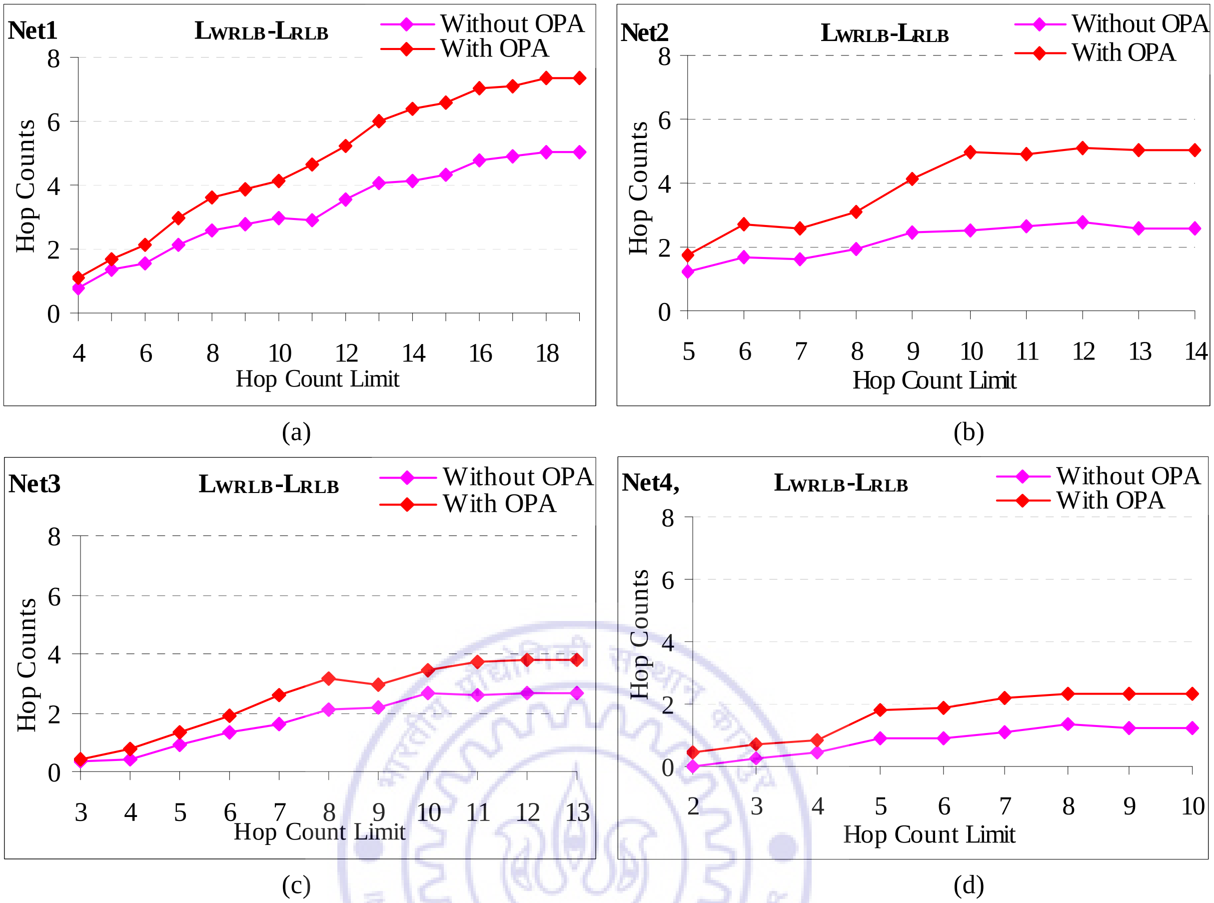


Figure 7-12 Reduction in the restored path lengths for various hop count limits without and with OPA for (a) Net1, (b) Net2, (c) Net3 and (d) Net4

The effects with different hop count limits for all the test networks are shown in Fig. 7.12. The difference between L_{WRLB} and L_{RLB} without OPA and with OPA has been compared and for all the cases use of OPA has resulted in better performance.

The performance for average nodal degree is slightly different (Fig. 7.13) and needs some explanation. Initially for $\overline{d} < 2.4$, the performance with OPA is almost similar to that of without OPA. This is due to the fact that with these values of $\overline{d}$, usually copies of just one *p*-cycle are there and no choices of *p*-cycles for OPA.. Hence, the use of OPA does not have any advantage in this scenario. However, as $\overline{d}$ increases the advantage of using OPA becomes evident (Fig. 7.13).

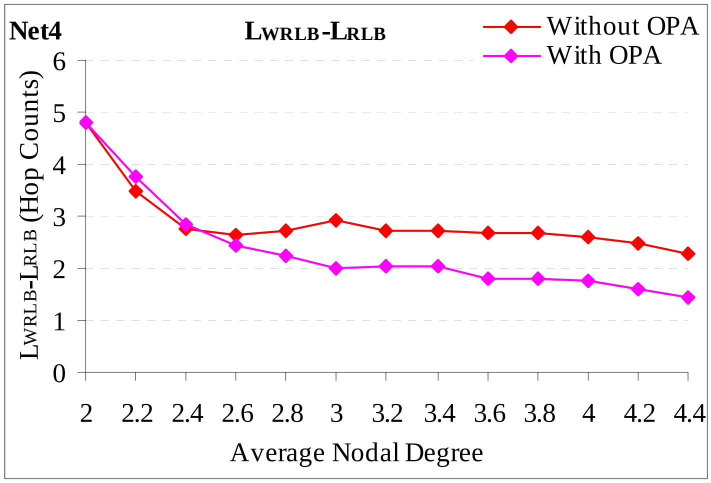


Figure 7-13 Reduction in the restored path lengths without and with OPA with variations in average nodal degree $\bar{d}$

The reduction in the restored path lengths has been shown for $\bar{d}$ = 2.0, 3.0 and 4.0 without and with OPA in Fig. 7.14. There is absolutely no difference for $\bar{d}$ = 2.0 as there will be only one *p*-cycle for this case and therefore no choices of *p*-cycles for OPA. The difference is more for $\bar{d}$ =3.0 and 4.0 with OPA as in other cases.

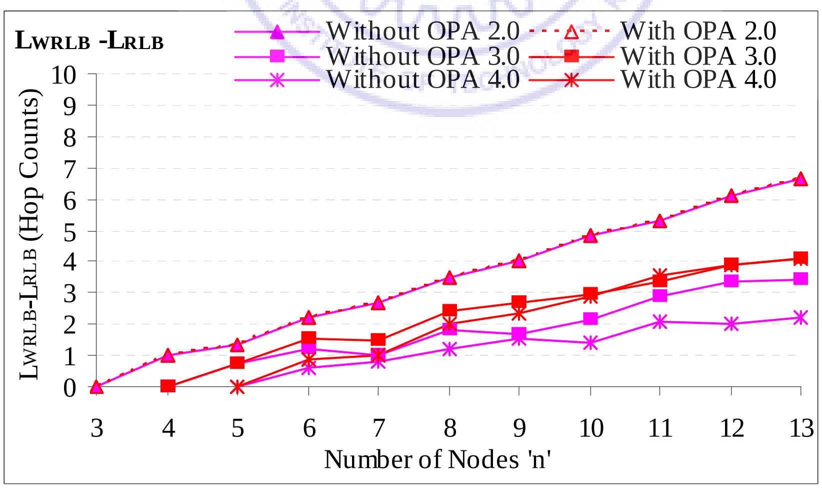
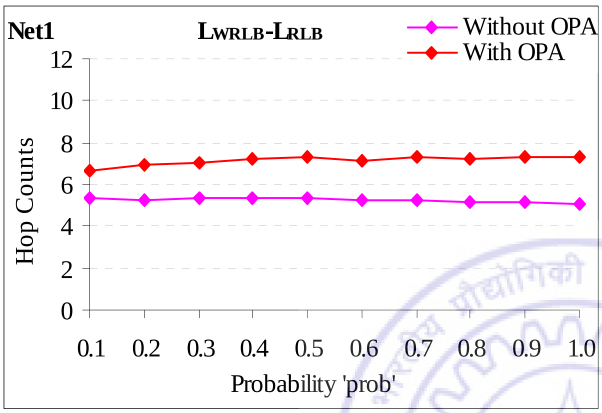
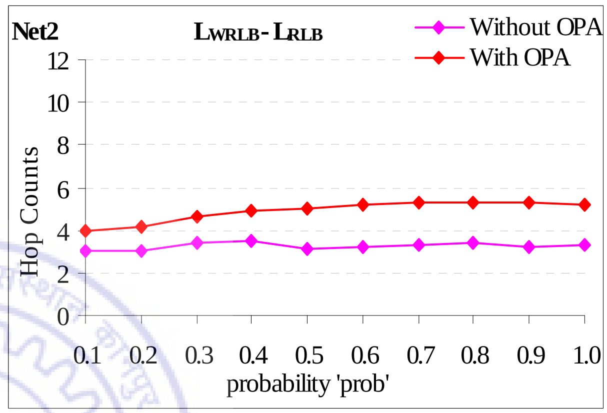


Figure 7-14 Reduction in the restored path lengths without and with OPA with number of nodes in the network for constant $\bar{d}$

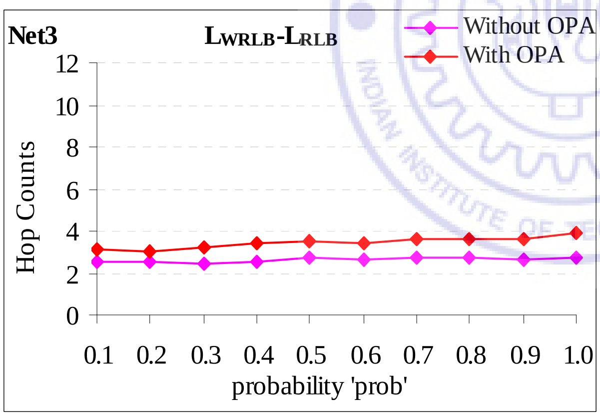
The performance improvement with various traffic distributions has also been consistent. For light traffic loads, the reduction in the restored path lengths with OPA is slightly less as compared to higher traffic loads. The reason has been same as explained in section 7.3.5. Again, for all the traffic loads RLBOPA has outperformed the RLB in terms of reduction in the restored path lengths (Fig. 7.15).



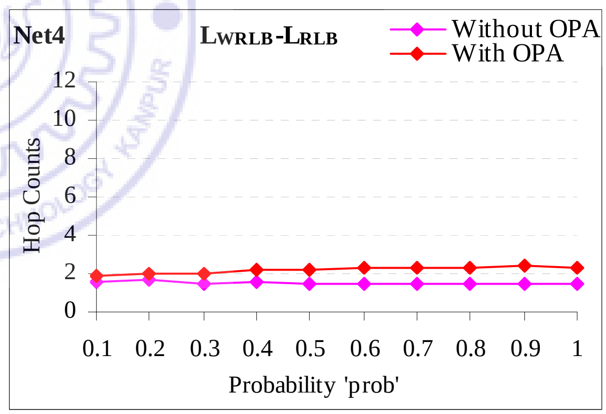
(a)



(b)



(c)



(d)

Figure 7-15 Reduction in the restored path lengths without and with OPA with traffic load for (a) Net1, (b) Net2, (c) Net3 and (d) Net4

The dual failure restorability with RLB and with RLBOPA has been compared in Fig. 7.16. For all the networks, with same spare capacity as required for single protection more percentage of links can be protected against dual failure with RLBOPA as compared to with RLB. The spare capacity requirement for 100 % dual failure restorability is also less with RLBOPA as compared to that of with RLB.

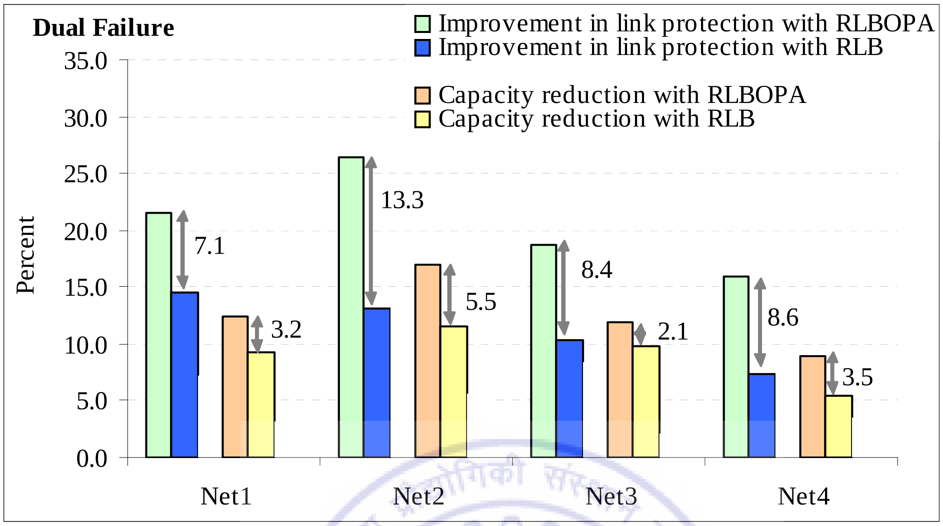


Figure 7-16 Improvement in the dual failure restorability with RLBOPA

The spare capacity requirements for single and dual failure restorability with and without OPA have been given in Table 7.15.

Table 7-15 The requirement of spare capacity for single and dual failure restorability

Test Networks	Working capacity	Spare capacity				
		Single failure	Dual failure			
			Without OPA		With OPA	
			Without RLB	With RLB	Without RLB	With RLB
Net1	984	754	2002	1700	1980	1590
Net2	390	286	734	612	734	556
Net3	316	194	514	426	514	408
Net4	142	70	192	170	190	156

Dual failure restorability based on span protection has also been reported in [150]. Our scheme can be compared with that of [150] in terms of capacity requirements. We have compared the spare to working capacity ratio in both the schemes. The minimum ratio is 1.89 for National network given in [150], for other two networks of [150], the above ratio is even higher for dual failure restorability for all possible failure combinations. Whereas in our case, the maximum value of this ratio is 1.62 with RLBOPA and 2.01 with WRLBOPA, for the test network Net1. Therefore, the capacity efficiency obtained with RLBOPA is better.

7.5 RELIABILITY ANALYSIS OF PATHS WITH RLBOPA

The reliability of the *p*-cycles has been discussed in section 4.2.5 and is not found to be very good. The main reason for poor reliability is the longer path lengths with *p*-cycle restoration. The restored path lengths can be reduced with removal of loop backs. We have done the reliability analysis of the paths with RLB, WRLB, RLBOPA and WRLBOPA [151]. The models used for reliability analysis are described below.

7.5.1 MODELS FOR RELIABILITY ANALYSIS

Let us consider the path– 1, 2, 3, 4 from source 1 to destination 4 (Fig. 7.17). It has three links 1–2, 2–3 and 3–4 protected with *p*-cycle paths n_1, n_2, and n_3 respectively (without any loop backs). The path will remain operational till any one of the following conditions holds.

Condition 1: All the links 1–2, 2–3 and 3–4 do not fail (Case I, Fig. 7.17(a)).

Condition 2: If link 1–2 fails then n_1 , 2–3 and 3–4 do not fail (Case II, Fig. 7.17(b)).

Condition 3: If link 2–3 fails then 1–2, n_2 and 3–4 do not fail (Case III, Fig. 7.17(c)).

Condition 4: If link 3–4 fails then 1–2, 2–3 and n_3 do not fail (Case IV, Fig. 7.17(d)).

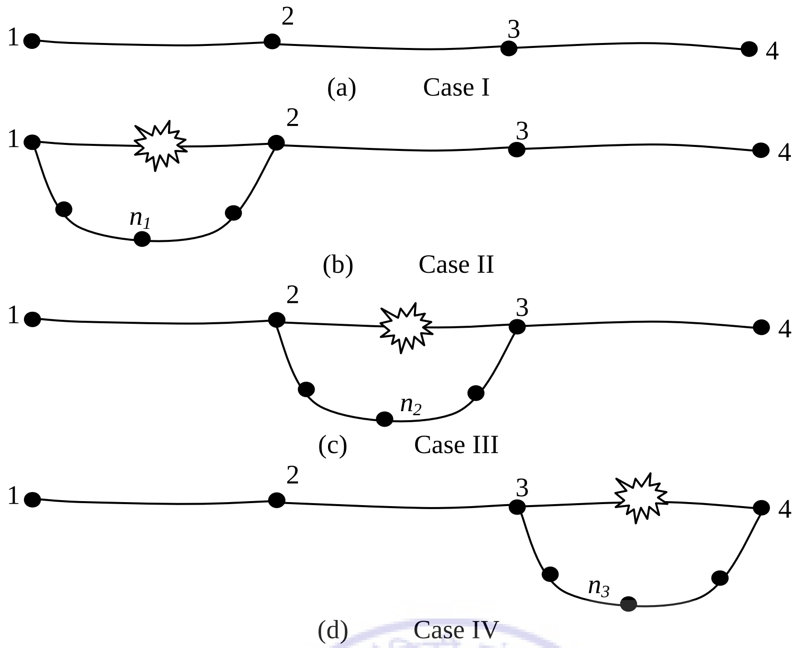


Figure 7-17 Reliability of a path with *p*-cycle protection

We are assuming that only one failure in the network can always be protected. The second failure can sometimes be protected in reality. Assuming second failure cannot be protected, we get a lower bound on reliability. Under the above assumption, the reliability for each of the above conditions will be

$$P(1) = P(X_{1,2}) \times P(X_{2,3}) \times P(X_{3,4}) \tag{7.1}$$

$$P(2) = (1 - P(X_{1,2})) \times P(n_1) \times P(X_{2,3}) \times P(X_{3,4}) \tag{7.2}$$

$$P(3) = (1 - P(X_{2,3})) \times P(n_2) \times P(X_{1,2}) \times P(X_{3,4}) \tag{7.3}$$

and $P(4) = (1 - P(X_{3,4})) \times P(n_3) \times P(X_{1,2}) \times P(X_{2,3})$ respectively. (7.4)

where $X_{1,2}$, $X_{2,3}$ and $X_{3,4}$ represent the successful operation of links 1–2, 2–3 and 3–4 respectively and $P(X_{1,2})$, $P(X_{2,3})$ and $P(X_{3,4})$ represent the respective probabilities of successful operation i.e. reliability of links 1–2, 2–3 and 3–4 respectively, assuming single failure at a time. The *p*-cycle paths n_1, n_2, and n_3 are series connection of links. The reliabilities of *p*-cycle paths n_1, n_2, and n_3 will be P(n_1), P(n_2), and P(n_3) respectively expressed as

$$P(n_j) = \prod_{\forall l \in [n_j]} P(X_l) \tag{7.5}$$

where P(X_l) is the reliability of link l falling in path n_j and [n_j] represents the set of links in *p*-cycle path n_j. Thus reliability of the path can be expressed as

$$P(1,4) = P(1) + P(2) + P(3) + P(4) \tag{7.6}$$

as each of the possibilities are mutually exclusive. The Equation 7.6 can be generalized for any path W having links indexed by j and every link is protected with a corresponding *p*-cycle path n_j, as

$$P(X) = \prod_{\forall j \in [W]} P(X_j) + \sum_{\forall j \in [W]} \left(\left(1 - P(X_j)\right) \times \left(\prod_{\forall l \in [n_j]} P(X_l) \right) \times \left(\prod_{\substack{\forall k \in [W], \\ k \neq j}} P(X_k) \right) \right)$$

……………………………………………………………………………………………...(7.7)

where X_l represents successful operation of l^{th} link in *p*-cycle path- n_j protecting link j of the path W and [W] represents the set of links in the working path. The Equation 7.7 has been derived assuming that there are no loop backs in the protection path provided by *p*-cycles. However, in the real scenario there may be loop backs in the restored paths with *p*-cycles (Fig 7.18 (b) and (d)).

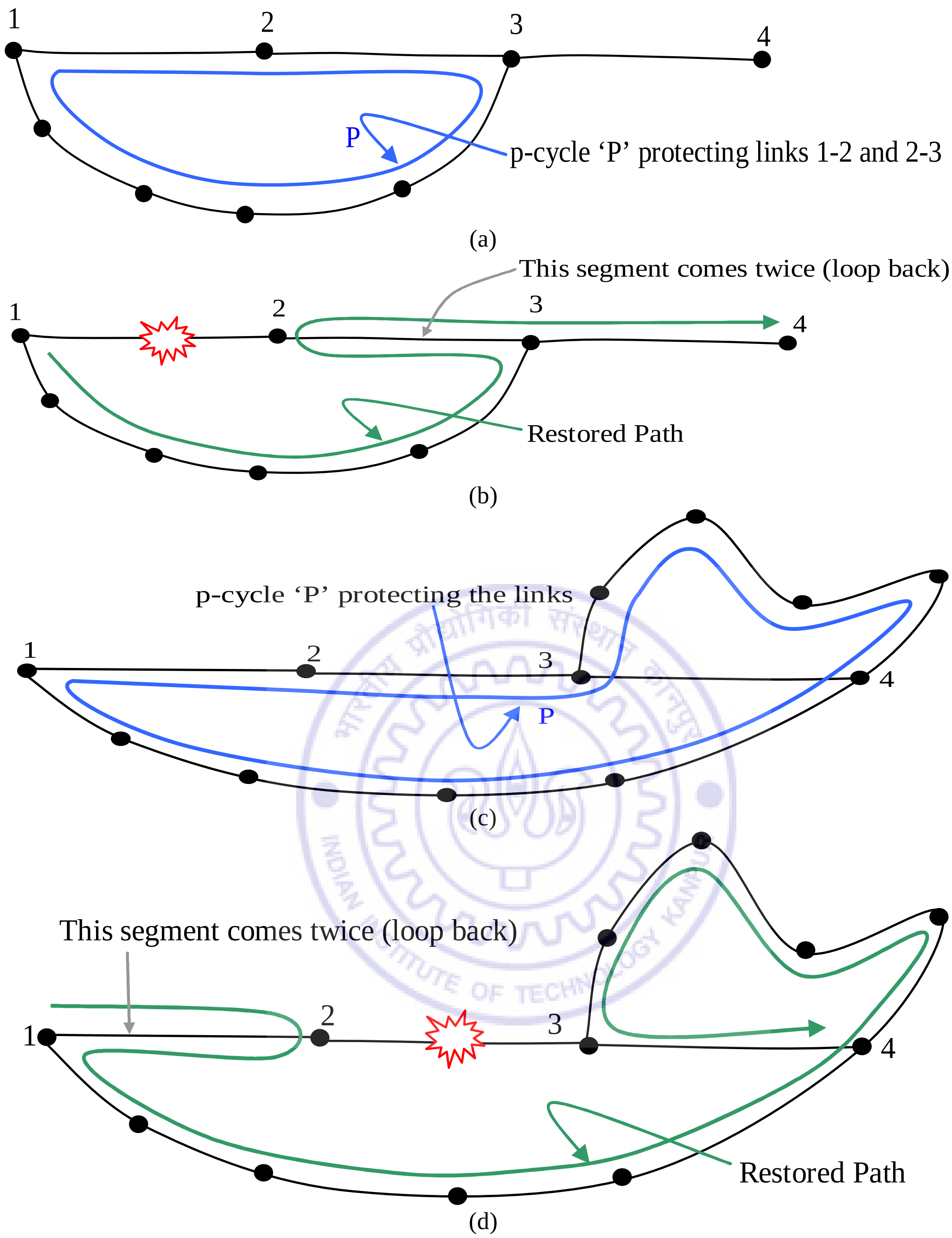
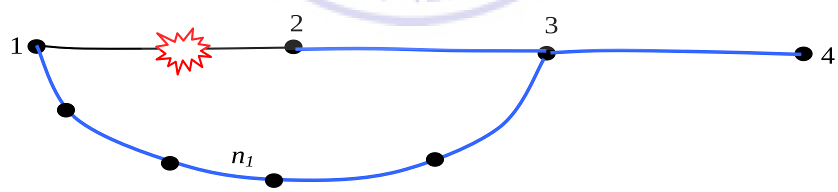


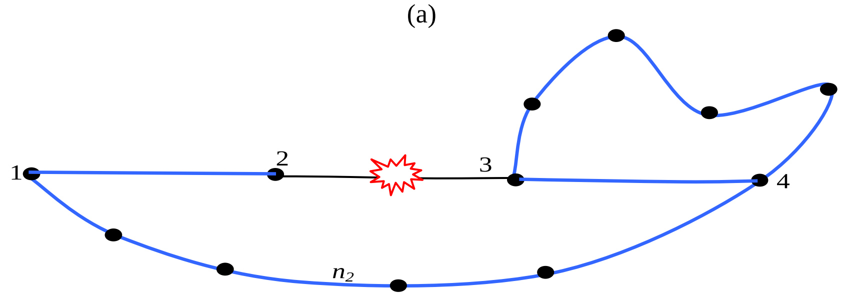
Figure 7-18 Loop backs in the restored path

We are considering the optical networks, for which usually span failure occurs and span failure means failure of all the links in that span. Hence, both links *i-j* and *j-i* will fail simultaneously if there is failure in the span *i, j*. In the presence of loop backs, sometimes the restored path might traverse a link more than once. While estimating reliability, such links should be considered only once. Figure 7.19 (a) and (b) show the links which are considered to estimate the reliability. Hence, the link 2-3 in Fig.7.19 (a) and link 1-2 in Fig. 7.19 (b) will be used only once in the reliability calculations. Any link or segment should not be considered twice or more for reliability estimates. Thus the Equation 7.7, in the presence of loop backs, will be modified to

$$P(X) = \prod_{\forall j \in [W]} P(X_j) + \sum_{\forall j \in [W]} \left((1 - P(X_j)) \times \frac{\prod_{\forall l \in [n_j]} P(X_l) \times \prod_{\substack{k \neq j, \\ \forall k \in [W]}} P(X_k)}{\prod_{\forall l \in ([W] \cap [n_j])} P(X_l)} \right). \quad (7.8)$$



(a)



(b)

Figure 7-19 Segments to be used for reliability estimates without RLB

After RLB, the path will be 1, n_1, 3, 4 and 1, n_2, 4 (blue segments in Fig. 7.20 (a) and (b) respectively). The reliability in this case will be given by

$$P(X) = \prod_{\forall j \in [W]} P(X_j) + \sum_{\forall j \in [W]} \left(\left(1 - P(X_j)\right) \times \left(\prod_{\forall i \in [S_{sj}]} P(X_i) \right) \times \left(\prod_{\forall k \in [P_{sj}]} P(X_k) \right) \times \left(\prod_{\forall l \in [D_{sj}]} P(X_l) \right) \right)$$

…………………………..(7.9),

where $[S_{sj}]$ is the set of links from the path segment from source to the upstream node of the failed span, $[P_{sj}]$ is the set of links from *p*-cycle and $[D_{sj}]$ is the set of links from path segment from downstream node of the failed span to destination, which are used to restore the failed span with removal of loop backs. With RLBOPA also, the model remains same (Fig. 7.20) as OPA only selects the *p*-cycle path to protect a working path. The Equation 7.8 and Equation 7.9 have been used for estimating the reliability of the paths before and after RLB respectively. The results are shown in Fig. 7.21.

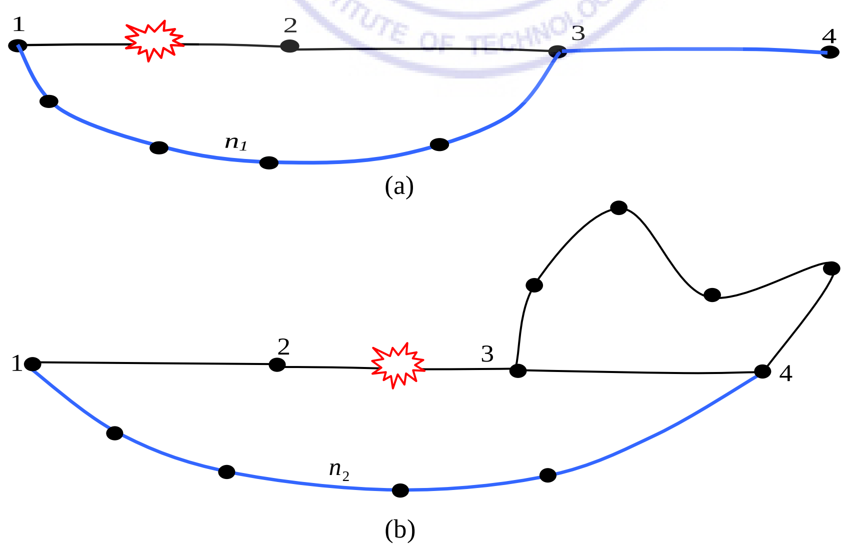


Figure 7-20 Models used for reliability estimates with RLB

7.5.2 RESULTS OF RLB ON PATH RELIABILITY

The reliability of every span of the network has been assumed to be 0.999, i.e. probability of failure as 0.001 and the reliability of the paths has been calculated using Equation 7.8 before removal of loop back i.e. WRLB. The paths are grouped on the basis of their length i.e. the number of hops in the working path and average value of reliability is calculated for each of these groups of paths. The paths with one hop count have not been included in the results, as for these paths, there is absolutely no change in the reliability. In the restored paths of one hop count paths, there will not be any loop backs and hence, the restored path lengths remain same before and after RLB.

The performance of WRLB, RLB, WRLBOPA and RLBOPA are shown in Fig. 7.21. The reliability of a path is decreasing with increase in the number of hop counts in the path for WRLB and WRLBOPA for all the test networks as expected from Equations 7.8 and 7.9. However, as a result of RLB and RLBOPA, the reliability of even longer paths is approaching to that of the smaller paths. The improvement in reliability is much more for longer paths as compared to smaller paths, as loop backs will be more with more hop counts in a path. Another observation is smaller values of reliability for longer paths with WRLBOPA than with WRLB. This suggests that with OPA to get minimum restored path lengths after removal of loop backs, usually longer *p*-cycle paths are allocated to longer working paths. This will give rise to longer loop backs and hence, the final path after removal of loop backs will be smaller. Further, as expected, the highest values of reliabilities are obtained invariably with RLBOPA, proving its superiority.

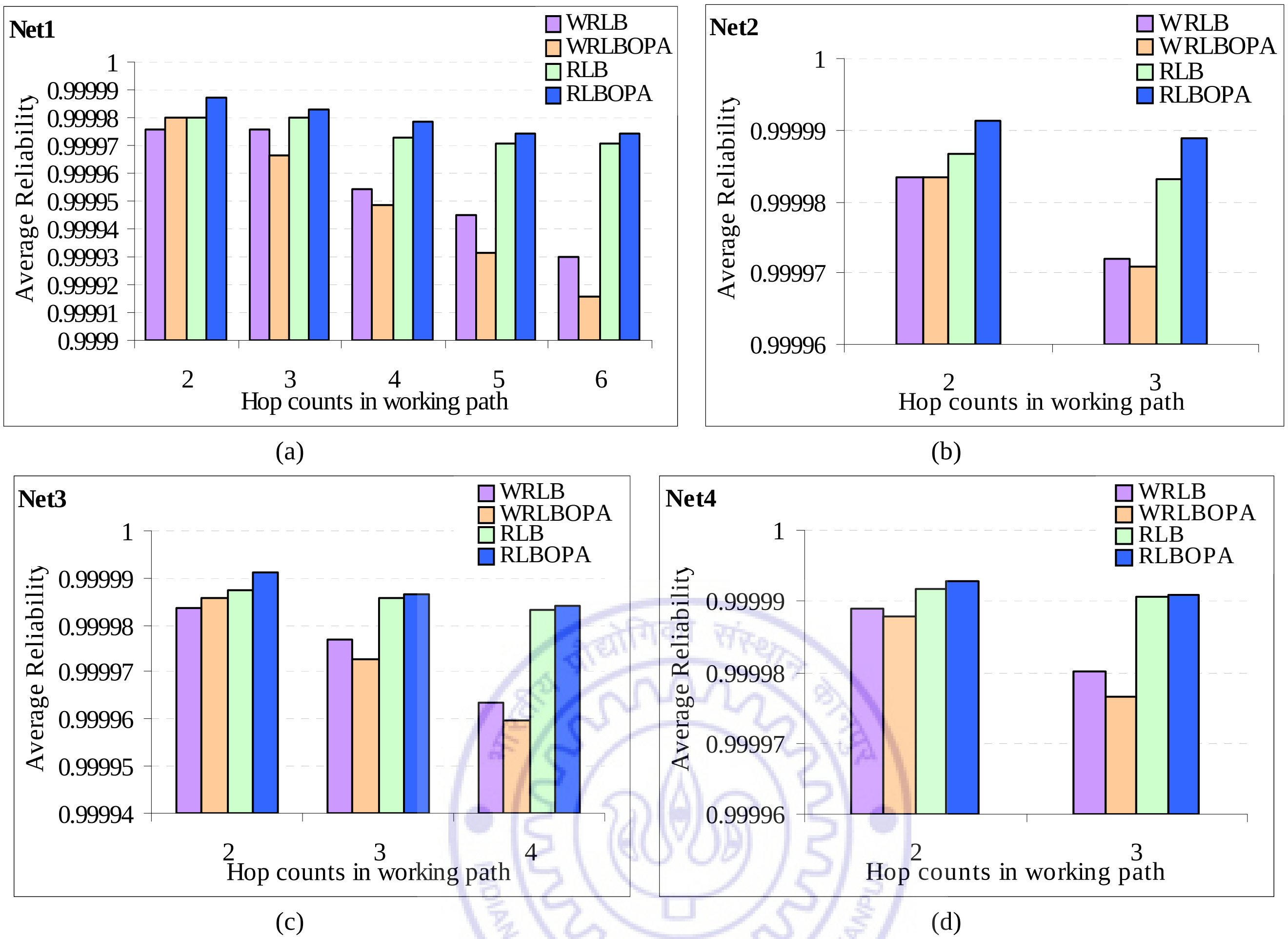


Figure 7-21 **Reliability of paths with RLB, WRLB, RLBOPA and WRLBOPA for (a) Net1, (b) Net2, (c) Net3 and (d) Net4**

7.6 SUMMARY

The *p*-cycle is a very promising technique of optical layer protection with relatively longer restored path lengths. To deal with the restored path length issue, RLB has been further strengthened with OPA, a method for allocation of already found *p*-cycles to the paths passing through the failed span to minimize the total restored path lengths. RLBOPA have been tested for various networks and for various methods of the *p*-cycle formation. The effects of the schemes have been studied by varying average node degree $\overline{d}$, number of nodes in the network '*n*' and traffic load. The study has been further extended for dual failure survivability.

On the basis of the results, it is evident that effectiveness of RLB increases with OPA for all the cases. With SCO model, the reduction in the path lengths has increased from about 32% with RLB to 51% with RLBOPA for Net2 (Table 7.14). Even for other networks and other conditions, the reduction with OPA is always significant. The minimum reduction with RLBOPA is about 35% for Net4 from 25 % with RLB with SCO model (Table 7.14). The difference in L_{WRLB} and L_{RLB} values are almost same for any of the test networks with all the models (SCO, H-L and DCPC) of *p*-cycle formation with OPA. The reduction is also independent of the traffic load. Thus, the performance of RLBOPA is consistent unlike RLB.

The RLBOPA while reducing the restored path lengths, also releases the redundant capacity which would have been otherwise unnecessarily engaged, resulting in longer restored path lengths. The released capacity can be effectively utilized for second failure restoration. In the dynamic traffic scenario, the released capacity may also be used for providing services to some other low priority traffic or for establishment of new lightpaths.

With the distributed protocol, the RLB for second phase reconfiguration can be implemented in any real network. The loop backs can be removed while retaining the ring like speed of the *p*-cycles. Thus, without compromising on any features of the *p*-cycle, restoration can be provided with significantly smaller restored path lengths using our RLBOPA scheme for second phase reconfiguration.

The reduction in the restored path length reduces the propagation delay, excessive signal degradation and increases the reliability of the restored path in the event of second failure. The increase in reliability is more for the paths which are having less reliability without RLB. Hence, with RLB, all the paths can have almost same order of reliability.

CHAPTER 8

SPECIALIZED PROTECTION TECHNIQUES WITH *P*-CYCLES[14]

So far, the *p*-cycle based protections have been discussed mostly for single failure protection to all the traffic in all the spans without any discrimination. However, in any network, some specific protection requirements can always be there. These specific requirements may be for the weaker links of the network, or for some critical traffic in the network, or for the spans which are very heavily loaded. So far, the provisions to meet out these specific requirements with *p*-cycles based protection, have not been explored. In this chapter, such issues have been discussed and schemes have been proposed to satisfy the specific requirements with special types of protection using *p*-cycles. The specialized types of protections have been provided by making use of dedicated *p*-cycles and straddling relationship of *p*-cycles with specific spans.

8.1 SOME SPECIFIC PROTECTION REQUIREMENTS

The specific protection requirements may be categorized as follows.

[14] This chapter is originated from the earlier published work [136], [152]

8.1.1 CATEGORY I

Under this category, the spans with low availability may be placed. The spans with small MTTF (mean time to failure) will fall under this category. These are the spans where failure is very frequent. These may include spans passing through densely populated cities, or passing through earthquake prone areas etc.. The failure on these spans will disrupt the network services quite often. They need some special protection.

Similarly spans with high MTTR i.e. mean time to repair will also come under this category. The undersea spans are one of the examples of high MTTR. Due to long repair times, the network services are affected for a long duration of time after failure of these spans. If second failure occurs during the failure of these spans, then the network services will be disrupted. Therefore, some provisions have to be there for taking care of these spans. We can call them low availability spans (LAS).

If there is one LAS, then we can consider that most of the time, the network is under one failure condition, and it is operative without any protection against second failure. During the off time of the LAS, the traffic on this span is restored as network is provisioned to survive one failure. The traffic which was being protected by the *p*-cycles which are consumed to restore the traffic through LAS, is now unprotected. At the same time, the traffic which was assigned protection with *p*-cycles passing through LAS, is also unprotected as the *p*-cycles will be broken during off time of the LAS. Thus, to retain the protection of other traffic during off time of LAS, two strategies have to be used. First, the traffic passing through the LAS has to be provided dual protection in such a way that protection to other traffic will not be affected. Secondly, the *p*-cycles which are used to provide protection to traffic other than the traffic of LAS, should not break down during the off time of LAS.

8.1.2 CATEGORY II

There may be some traffic in the network which is critical[15]. This critical traffic may require dual failure protection or high reliability, or guaranteed services etc.. Various types of real time applications e.g. remote monitoring and control, remote surgery may come under this category. To allow such type of traffic to pass through the network, the service providers have to provide differentiated reliability as per the demand of the customer to satisfy some service level agreements.

The network can be provisioned with dual failure protection for all the traffic. However with this option, the spare capacity requirement will be quite high (Table 8.1). The capacity requirement for dual failure protection is almost double than that of the single failure protection. Therefore, this option is not economical. Hence, the dual failure protection can be provided only to the critical traffic.

Table 8-1 The requirement of spare capacity for dual failure protection with RLBOPA

Test Networks	Working capacity A	Spare capacity B		Capacity redundancy B*100/A	
		Single failure	Dual failure	Single failure	Dual failure
Net1	984	754	1590	76.6	161.6
Net2	390	286	556	73.3	142.6
Net3	316	194	408	61.4	129.1
Net4	142	70	156	49.3	109.9

The specific protection requirements may be defined as per the needs of the customers and the capability of network operators (service providers). The above issues related with

[15] We are assuming that the amount of critical traffic is in the units of one lightpath.

protection can be resolved with the help of special protection using the dedicated *p*-cycles [119], [120] and maintaining the straddling relationship of *p*-cycles with specified spans.

8.2 DEDICATED *P*-CYCLES

Till now we are working with the *p*-cycles which can provide protection to all the on-cycle and the straddling spans simultaneously on the shared basis. Thus, these *p*-cycles come under the category of shared span protection and are having good efficiency. On the contrary the dedicated *p*-cycles are used to provide protection to a single span without any sharing. Thus, the traffic on all other on-cycle and straddling spans of the *p*-cycle is not protected by this dedicated *p*-cycle. At the same time, spare capacities are required on all the on-cycle spans for the formation of *p*-cycle. Therefore, dedicated *p*-cycles will not be capacity efficient but can provide dedicated protection. These *p*-cycles can also have on-cycle and straddling span relationships with the span which requires specific protection.

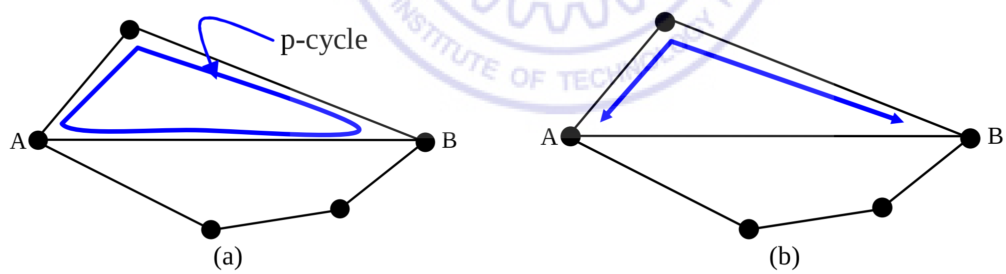


Figure 8-1 Dedicated *p*-cycle protection to the on-cycle span AB, (a) dedicated *p*-cycle (b) protection path provided by *p*-cycle

8.2.1 ON-CYCLE DEDICATED PROTECTION

The *p*-cycles are formed in such a way that the span which needs dedicated protection, is having on-cycle relationship with the *p*-cycles (Fig. 8.1). The protection is almost similar to link disjoint path protection (LDPP) used for protecting the span. The difference is in terms of speed. In case of LDPP, the links have to be connected after the event of failure, whereas, in case of *p*-cycles, all the links are pre-connected and only two switching actions at the end nodes of the failed span are required to restore the traffic. The speed of restoration will be faster with *p*-cycles as compared to LDPP. However, the speed of restoration will be same as with 1+1 duplicated path protection. Now, there will be a difference in terms of spare capacity requirement. The *p*-cycles require spare capacity on all the on-cycle spans, including the one to which it is providing dedicated path protection. Hence, in terms of spare capacity requirement, 1+1 duplicated path protection is a better option as spare capacity is not required on the span which is being protected. Therefore, dedicated *p*-cycles will not be used to provide protection to on-cycle spans.

8.2.2 DEDICATED STRADDLING SPAN PROTECTION

The dedicated *p*-cycle having straddling span relationship with the given span will be used to provide dual failure protection to one unit of traffic on the straddling span. In this case, there are two link disjoint left and right (LP and RP) paths of the *p*-cycle to provide protection to one unit of traffic (Fig. 8.2). Now, the difference with 1:1 dedicated path protection is in terms of speed as well as number of paths. With dedicated *p*-cycles having straddling span relationship, there are two link disjoint paths. The *p*-cycle based protection is preferred due to its speed (because of pre-connected spare capacity) and double protection. It should be noted that it will be same as 2+1 duplicated path protection in terms of speed as well as capacity.

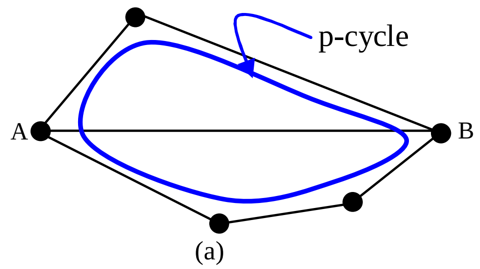


Figure 8-2 Dedicated *p*-cycle protection to straddling span, (a) dedicated *p*-cycle (b) two paths – LP and RP provided by dedicated *p*-cycle

The dedicated *p*-cycles will provide guaranteed dual failure protection. If first failure is on the given specific span, then the LP of the *p*-cycle is used to provide protection and RP will be used when second failure disrupts the LP. If first failure is on any one of the on-cycle span then either the LP or the RP which is having the failed span will fail and the other one will be used in case of second failure disrupting the traffic on the span. However, for guaranteed dual failure protection with dedicated *p*-cycles, the capacity efficiency of shared *p*-cycles will be sacrificed as with dedicated and duplicated path protections.

8.3 SPECIALIZED PROTECTION SCHEMES FOR CATEGORY I

The spans with low availability have been placed under this category. With single failure protection, the first failure on the LAS can be protected. However, the second failure, when the LAS is unavailable cannot be protected. We have proposed two schemes to provide specialized protection to the LAS so that network services will not be disrupted even during the second failures when the LAS is unavailable. In the first case, we have simply removed the LAS, and in the second case, dedicated *p*-cycles have been used. The details are given below.

8.3.1 CASE I- REMOVAL OF LOW AVAILABILITY SPAN

First, we have simply removed the LAS. All the traffic in the network is routed on the remaining spans of the network using Dijkstra's algorithm as usual. Then spare capacity optimization (SCO) model is used to find the set of *p*-cycles which can provide protection to all the working capacity with minimum spare capacity. By removal of LAS, first failure on this span has been taken care of by avoiding it, and the second failure is being protected with the set of *p*-cycles found with the SCO model. During simulations, one by one each span has been removed and the working and protection capacities have been found for the remaining spans. Then average has been calculated for each test network.

The working capacity requirement will surely be increased as the one hop links on the LAS of the working paths are now replaced by links having more than one hop count. With increase in working capacity, spare capacity required for protection is also expected to increase. The advantage will be the overall improvement in the network services as the LAS has been removed.

8.3.2 CASE II- DEDICATED P-CYCLE PROTECTION

In this case, dedicated *p*-cycles have been used to deal with the problem of LAS. The dedicated *p*-cycles are to be used to provide protection to one span only (i.e. LAS); hence, smallest *p*-cycles having straddling span relationship with the LAS is selected among all the cycles of the network. At the same time, for protection of traffic on other spans, care has been taken to find the set of *p*-cycles such that none of them will pass through the given LAS. This will ensure that protection to all other spans will not be broken during failure of the LAS. The set of *p*-cycles with these requirements can again be found with ILP model developed by us with modifications in the SCO model. The modified ILP model called as dedicated *p*-cycle protection (DPP) model is given below.

- ***DEDICATED P-CYCLE PROTECTION (DPP) MODEL***

Sets used in this model are as follows.

W_i Set of working paths passing through failed span i indexed by r.

CS Set of low availability spans indexed by k.

S-CS Set of spans, excluding the low availability spans, indexed by j .

P_1 Set of all the *p*-cycles of the network indexed by p excluding the elements of P_3.

P_2 Set of *p*-cycles indexed by p_{spk}. The p_{spk} is the smallest *p*-cycle used for protection of low availability span k. The number of *p*-cycles in P_2 is equal to the number of LAS in the network.

P_3 Set of *p*-cycles passing through at least one member of CS.

Parameters used are as follows.

c_j Cost of span j (assumed to be one in our networks).

w_j Working capacity on span j .

ω_k Working capacity on low availability span k.

π_j^p Equal to 1 if *p*-cycle p crosses span j , otherwise 0.

$\Pi_j^{p_{spk}}$ Equal to 1 if *p*-cycle p_{spk} crosses span j , otherwise 0.

x_j^p Equal to 1 if the *p*-cycle p protects span j as on cycle span, equal to 2 if *p*-cycle p protects span j as straddling span and 0 otherwise (it will not provide protection to spans of set CS).

$\chi_k^{p_{spk}}$ Equal to 1 when *p*-cycle p_{spk} protects low availability span *k* as straddling span and 0 otherwise (it will not provide protection to any other span).

Variables used are:

sp_j Spare capacity required on span j.

n^p Number of unit-capacity copies of *p*-cycle *p* in the solution.

$n^{p_{spk}}$ Number of unit-capacity copies of *p*-cycle p_{spk} in the solution.

Minimize: $$\sum_{\forall j \in (S-CS)} c_j . sp_j \qquad (8.1)$$

Subject to:

$$w_j \le \sum_{\forall p \in P_1} x_j^p . n^p \qquad \forall j \in (S-CS), \qquad (8.2)$$

$$\omega_k \le \sum_{\forall p \in P_2} \chi_k^{p_{spk}} . n^{p_{spk}} \qquad \forall k \in CS, \qquad (8.3)$$

$$sp_j = \sum_{\forall p \in P_1} \pi_j^p . n^p + \sum_{\forall p_{spk} \in P_2} \Pi_j^{spk} . n^{p_{spk}} \qquad \forall j \in (S-CS), \qquad (8.4)$$

$$x_k^p = 0 \qquad \forall p \in P_1, \quad \forall k \in CS, \qquad (8.5)$$

$$n^p \ge 0 \text{ and } n^{p_{spk}} \ge 0 \qquad \forall p \in P_1, \quad \forall p_{spk} \in P_2. \qquad (8.6)$$

The objective function of Equation (8.1) minimizes the total spare capacity used in the formation of *p*-cycles. Equation (8.2) ensures that all the working capacity of all the spans except LAS, is protected, and Equation (8.3) ensures that double protection is available for LAS. Equation (8.4) provides sufficient spare capacity on every span to form the *p*-cycles. The traffic on the LAS should not be protected by any *p*-cycle other than the dedicated *p*-

cycles; this is ensured by Equation (8.5). The spare capacity is not required on the LAS, as *p*-cycles passing through these spans are not used to provide protection to any of the traffic on any of the spans.

8.3.3 Performance Comparison of Case I and Case II

In the two cases discussed above, we are providing specialized protection for LAS. The performance of both these cases can be compared on the basis of speed of restoration and capacity requirement. The model in Case I provides single failure restorability to all the traffic of the remaining spans with ring like speed of *p*-cycles. LAS is not at all used.

In the DPP model of Case II, we are providing sufficient spare capacity so that network can survive first failure among the spans other than LAS's even when one or more LAS's are not available due to occurrence of failures on them. In this case also, the ring like speed of restoration will be there. In our calculation, we have considered only one LAS at any point of time. We have considered each span as LAS one by one and DPP model has been used to find the spare capacity to provide the specialized protection. There are some spans which cannot become straddling spans as the degree of one of their incident node is two. These spans cannot be removed from the network as their removal will leave at least one node un-connected. Therefore, these spans cannot be provided specialized protection of LAS, and entries for these spans are shown as dash in the Tables 8.2 to 8.5. The capacity required in both the cases has been shown in Tables 8.2 to 8.5 for the test networks. The average capacity requirement has also been compared in Fig. 8.3.

Table 8-2 The requirement of capacity in Case I and Case II for Net1, with single LAS

Net1						
	Working capacity		**Spare capacity**		**Total capacity**	
LAS Span No.	**Case I**	**Case II**	**Case I**	**Case II**	**Case I**	**Case II**
1	------*	------	------	------	------	------
2	988	984	856	862	1844	1846
3	1046	984	1046	1432	2092	2416
4	------	------	------	------	------	------
5	988	984	766	850	1754	1834
6	1006	984	922	974	1928	1958
7	1002	984	990	934	1992	1918
8	1014	984	824	964	1838	1948
9	------	------	------	------	------	------
10	1024	984	876	1042	1900	2026
11	1000	984	816	874	1816	1858
12	------	------	------	------	------	------
13	1002	984	810	1146	1812	2130
14	1012	984	1142	1370	2154	2354
15	994	984	830	1024	1824	2008
16	1016	984	1184	1124	2200	2108
17	1050	984	1402	1728	2452	2712
18	1010	984	826	894	1836	1878
19	1052	984	990	1262	2042	2246
20	1014	984	1010	936	2024	1920
21	------	------	------	------	------	------
22	------	------	------	------	------	------
23	------	------	------	------	------	------
24	------	------	------	------	------	------
25	------	------	------	------	------	------
26	------	------	------	------	------	------
27	1018	984	874	994	1892	1978
28	------	------	------	------	------	------

* The '------' are used for the spans which could not be provided specialized protection of LAS.

Table 8-3 The requirement of capacity in Case I and Case II for Net2, with single LAS

Net2						
	Working capacity		Spare capacity		Total capacity	
LAS Span No.	Case I	Case II	Case I	Case II	Case I	Case II
1	400	390	322	398	722	788
2	398	390	326	398	724	788
3	420	390	394	530	814	920
4	402	390	328	358	730	748
5	418	390	382	500	800	890
6	424	390	376	512	800	902
7	412	390	338	526	750	916
8	428	390	434	550	862	940
9	416	390	336	502	752	892
10	------*	------	------	------	------	------
11	------	------	------	------	------	------
12	422	390	382	486	804	876
13	------	------	------	------	------	------
14	436	390	434	594	870	984
15	------	------	------	------	------	------
16	400	390	298	446	698	836
17	400	390	290	366	690	756
18	404	390	312	440	716	830
19	404	390	308	356	712	746
20	398	390	302	370	700	760
21	398	390	302	328	700	718

* The ‘------’ are used for the spans which could not be provided specialized protection of LAS.

Table 8-4 The requirement of capacity in Case I and Case II for Net3, with single LAS

Net3						
	Working capacity		**Spare capacity**		**Total capacity**	
LAS Span No.	**Case I**	**Case II**	**Case I**	**Case II**	**Case I**	**Case II**
1	330	316	238	358	568	674
2	328	316	224	326	552	642
3	320	316	210	226	530	542
4	318	316	196	224	514	540
5	326	316	236	278	562	594
6	318	316	228	224	546	540
7	322	316	234	356	556	672
8	320	316	202	274	522	590
9	326	316	220	274	546	590
10	320	316	232	320	552	636
11	328	316	256	242	584	558
12	------*	------	------	------	------	------
13	324	316	216	264	540	580
14	------	------	------	------	------	------
15	------	------	------	------	------	------
16	324	316	224	294	548	610
17	336	316	256	338	592	654
18	------	------	------	------	------	------
19	320	316	226	224	546	540
20	322	316	246	230	568	546
21	324	316	194	264	518	580
22	326	316	194	254	549.6	593.4
23	320	316	202	210	548.6	588.7

* The '------' are used for the spans which could not be provided specialized protection of LAS.

Table 8-5 The requirement of capacity in Case I and Case II for Net4, with single LAS

Net4						
	Working capacity		Spare capacity		Total capacity	
LAS Span No.	Case I	Case II	Case I	Case II	Case I	Case II
1	146	142	98	146	244	288
2	148	142	70	136	218	278
3	144	142	82	94	226	236
4	144	142	82	86	226	228
5	146	142	108	94	254	236
6	146	142	78	126	224	268
7	144	142	76	94	220	236
8	144	142	74	94	218	236
9	146	142	92	118	238	260
10	144	142	70	86	214	228
11	144	142	76	102	220	244
12	148	142	84	102	232	244
13	144	142	78	94	222	236
14	144	142	70	94	214	236
15	144	142	72	78	216	220
16	144	142	72	86	216	228
17	144	142	74	78	218	220
18	144	142	70	92	214	234
19	146	142	88	94	234	236
20	144	142	72	86	216	228
21	148	142	72	110	220	252
22	146	142	80	94	276.7	298.4

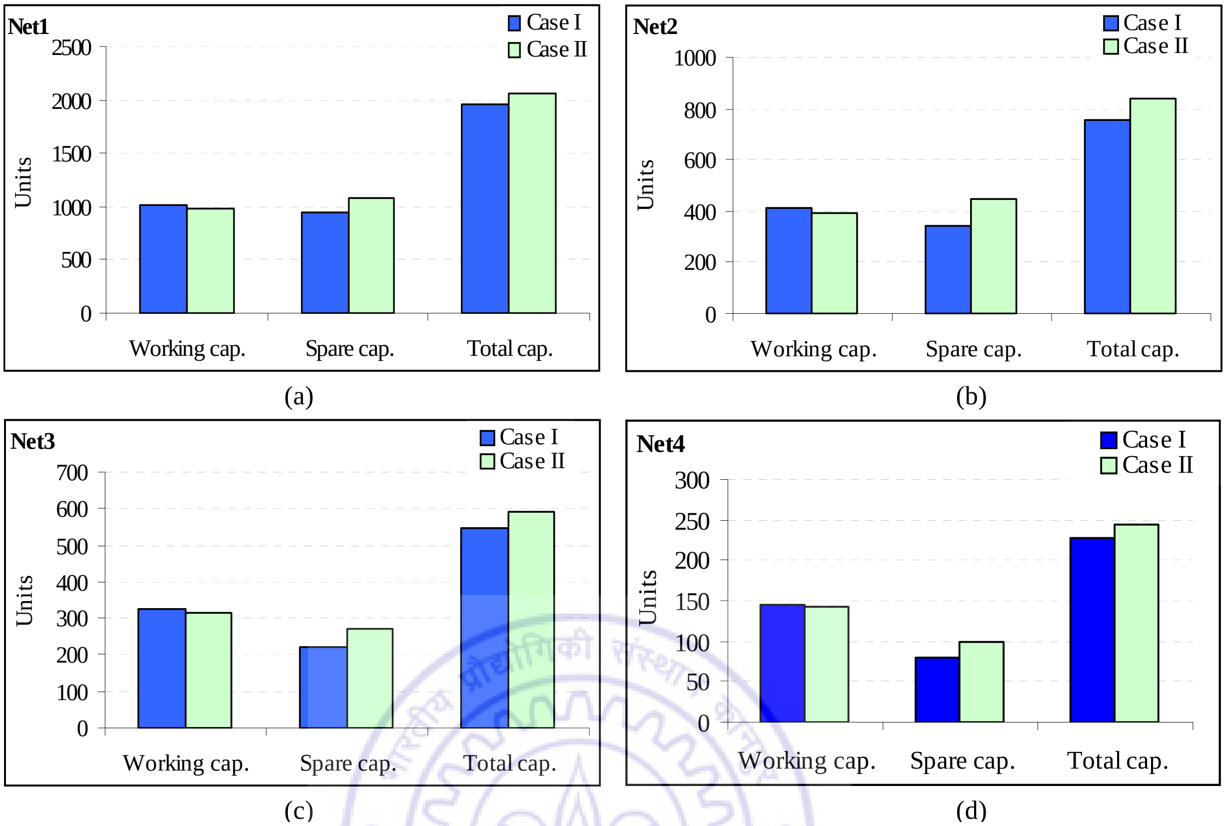


Figure 8-3 **Comparison of average capacity requirements for Case I and Case II, (a) Net1, (b) Net2, (c) Net3 and (d) Net4**

As evident from Tables 8.2 to 8.5, more working capacity is required with Case I for each span of all the test networks, as compared to Case II. However, the spare capacity required is not more for each of the span. In fact, for almost every span spare capacity required is less than Case II (except for span numbers 7, 16 and 20 in Net1 –Table 8.2, span numbers 6, 11, 19 and 20 in Net3 –Table 8.4, span number 5 in Net4 –Table 8.5). This is due to the fact that in Case I, we are having the optimum solution with SCO model, whereas in Case II, we are having additional constraints of dedicated *p*-cycles and the constraint of *p*-cycles not passing through LAS. Therefore, more spare capacity is required in Case II. The advantage with Case II is that we can use the LAS span. The traffic through the LAS is protected against dual failure subject to first failure on LAS. In general, if more than one LASs are there, then traffic is protected for failure of all LASs and single failure on any of the remaining spans (excluding LASs).

The specialized protection for low availability spans can now be selected from Case I and Case II. For most of the spans, the solution is to remove them from the network and design the network without this span. However, for some of the spans the most efficient solution is Case II, where dedicated *p*-cycles have been used to provide protection.

8.4 CATEGORY II PROTECTION WITH DEDICATED *P*-CYCLES

The *p*-cycle based protection provides single failure protection to all the traffic of the network by protecting every working path on each span. The complete path protection can also be provided using path protecting *p*-cycles [58], [59]. However, this type of path protection is also shared path protection and cannot guarantee dual failure protection.

The working paths in Category II can be provided guaranteed dual failure protection with dedicated *p*-cycles as shown in Fig. 8.4. The critical traffic from source node 2 to destination node 8 on working path -2, 10, 11, 8, is being protected by *p*-cycle -2, 3, 10, 6, 8, 0, 1, 2, with its left and right paths (LP and RP). The LP and RP both are not sharing any link with the working path, and the *p*-cycle is not providing protection to any span or path segment except the working path carrying the critical traffic, for which complete dual failure protection is guaranteed. In this manner, the critical path is protected against dual failures exclusively on the working path and on the protection paths (LP and RP) of p-cycle used for protection. The other failures in the network will not have any effect on the critical path. Thus, the reliability of the critical path is expected to be quite high.

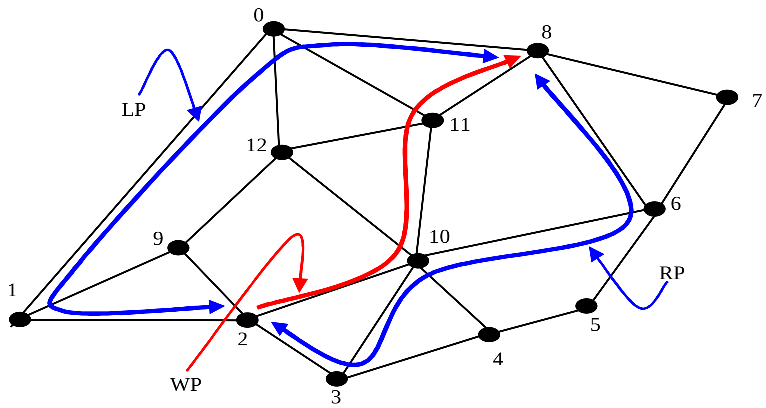


Figure 8-4 Guaranteed dual failure protection to critical path with dedicated *p*-cycle

With *p*-cycles, due to their property of pre-configuration, restoration can be provided with ring like speed in case of failures. At the time of setup of path protecting dedicated *p*-cycles, the end nodes (source node and destination node) of the working path will make the entries about the alternate paths through the dedicated *p*-cycle. As soon as, there is any failure on any link, both the end nodes will perform the switching and traffic will be switched over to one of the available dedicated *p*-cycle paths. In the following sections, we will study the effects of critical traffic protection with dedicated *p*-cycles, on the capacity requirement and on the reliability of the path.

The dual failure protection has also been considered in [132] for providing multiple quality of protection (QoP) classes. In [132], the straddling span protection has been used to provide dual failure protection to the links of the platinum working path. All the links of the platinum paths are having straddling relationship with the *p*-cycles used for this protection. One p-cycle may have many straddling spans and with the ILP formulation given in [132], same p-cycle may be used to protect many platinum working paths on all the different straddling spans. In this way, the p-cycle is having some amount of sharing among the platinum working paths. Even with this sharing, the platinum working path has been protected for dual failures in the network. But dual failures on platinum working path and its protection path exclusively may not be protected in many cases. Thus, guaranteed exclusive dual failure protection will not be available. Whereas, in our scheme, the complete path is having straddling relationship with a dedicated p-cycle and the same p-cycle cannot be used to provide protection to any other path or link. Hence, guaranteed exclusive dual failure protection can be provided.

8.4.1 CAPACITY REQUIREMENT FOR CRITICAL TRAFFIC PROTECTION

To find out the capacity requirement for providing exclusive dual failure protection to the critical traffic, the simulations have been done as follows. First, the smallest *p*-cycle which is fulfilling the following conditions has been found from the set of all the cycles in the network.

- The *p*-cycle and the working path should not share any common spans.
- The source and the destination nodes of the working path should have straddling span relationship with the *p*-cycle.

This is to be mentioned that the nodes having degree two cannot have *p*-cycles with straddling span relationship. Therefore, the paths which are originating or ending at any of these nodes cannot be provided guaranteed exclusive dual failure protection.

The working paths in the network which need to be provided exclusive dual failure protection, have been protected with dedicated *p*-cycles found as above. The links of the remaining paths have been provided protection with SCO model of the *p*-cycle formation as usual. The total capacity required for both is added and compared with the capacity required in the SCO model for protection of all the traffic. We have found the percentage of additional capacity required for dual failure protection per path.

The following variables are defined to determine the additional capacity.

N_w Total number of working paths in the network. With unit traffic matrix for n node network, this will be equal to $n(n-1)$.

N_1 Total number of paths carrying critical traffic which need to be provided dedicated *p*-cycle protection for guaranteed dual failure protection. Neither source, nor destination nodes are of degree 2 or less for these paths.

N_2 The number of paths[16] which are protected against single failure in the network using conventional *p*-cycles.

T_{sp} The spare capacity required for protecting all the traffic of the network with SCO model. The critical traffic is also provided only single failure protection in this case by considering it as normal traffic.

T_1 The spare capacity required for protecting N_1 critical paths of the network with dedicated *p*-cycles.

T_2 The spare capacity required for protecting normal traffic (N_2 paths) of the network with SCO model.

ΔT The percentage of additional capacity required for providing dual failure protection per path.

$$\Delta T = \frac{(T_1 + T_2 - T_{sp}) \times 100}{T_{sp} \times N_1}. \tag{8.7}$$

[16] One lightpath means that the lightpaths in both the directions have been provided critical path protection.

8.4.2 *RESULTS AND DISCUSSIONS*

The results for all the test networks with single critical path have been shown in Fig. 8.5. Every path is considered as critical path, if possible, one by one. ΔT is computed and averaged over all possible path choices, and then shown in Fig 8.5. It is clear from the figure that as the number of nodes in the network is increasing ΔT is decreasing. ΔT is small for large network as T_{sp} is large. Thus, with very small increase in the overall spare capacity, guaranteed dual failure protection with dedicated *p*-cycles can be provided to the critical traffic in the network.

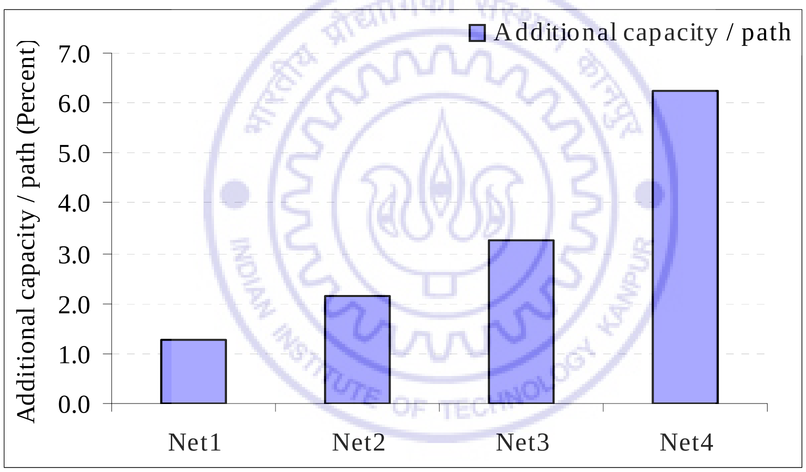


Figure 8-5 Additional capacity per critical path required for guaranteed exclusive dual failure protection for single critical path

Further, the ratio of spare to working capacity for different protections has been compared in Fig. 8.6. The working capacity for all the cases remains same as the total number of paths in the network is constant, and only type of protection is different. The spare capacity requirement for protection against single failure has been obtained with SCO model, without dual failure protection for critical paths. Next, we have shown the ratio of spare to working capacity for one critical path, 5 critical paths, and 10 critical paths. To obtain the results for 1, 5, and 10 critical paths, the paths have been selected randomly and then average is calculated. The above ratio has also been found for the maximum number of paths which can be provided critical path protection. On the same graphs, the ratio of spare to working capacity requirement for dual failure protection as obtained in section 7.3.6 and shown in Table 7.15, with RLBOPA and WRLBOPA has also been shown.

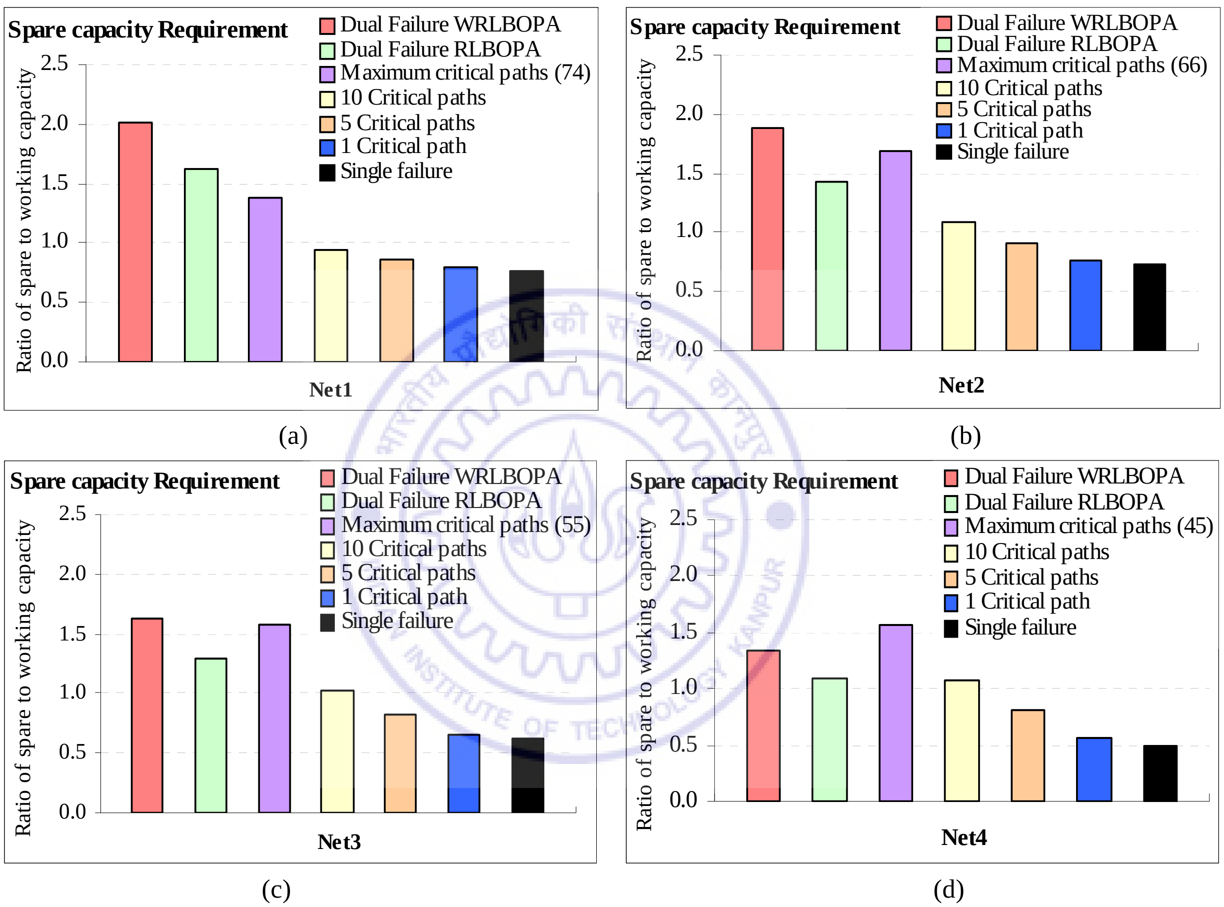


Figure 8-6 Ratio of spare to working capacity requirements for different types of protection for (a) Net1, (b) Net2, (c) Net3, and (d) Net4

It is evident from Fig. 8.6 that when the number of critical paths in the network is small, it is better, in terms of spare capacity requirement, to provide them dual failure protection of critical paths. As expected, the requirement of spare capacity is increasing with increase in the number of critical paths. For Net2, Net3 and Net4, it is interesting to note that if maximum number of possible critical paths are to be provided critical path protection, then it is better to provide dual failure protection with RLBOPA to all the working capacity of the network instead of providing critical path protection. In case of Net4, the dual failure protection to all the working capacity can be provided with almost same spare capacity as required for providing critical path protection to 10 paths. Hence, in this network if there are more than 10 paths which require dual failure protection, then it is better to provide dual failure protection to all the working capacity. For Net1, the maximum number of paths which can be provided critical path protection are less (74 out of 171), hence, all of them can be provided critical path protection with smaller spare capacity requirement as compared to dual failure protection with RLBOPA.

8.4.3 IMPROVEMENT IN RELIABILITY

The effect of dedicated *p*-cycle based guaranteed dual protection on the reliability of the paths passing through the critical spans, has been studied. The reliability of the path has been found with the model for shared *p*-cycle protection (using Equation 7.8 as in section 7.5) and then, with dedicated *p*-cycle protection. With dedicated *p*-cycle, the path reliability is found using Equation 2.4 of section 2.3.3 as

$$P(X)=1-\left[1-\prod_{j=1}^{n_1}P(X_{1j})\right]\times\left[1-\prod_{j=1}^{n_2}P(X_{2j})\right]\times\left[1-\prod_{j=1}^{n_3}P(X_{3j})\right], \qquad (8.8)$$

where 1 is the working path, 2 and 3 are the LP and RP of the *p*-cycle respectively. The number of elements in working path, LP and RP are n_1, n_2 and n3 respectively.

The calculated reliabilities are shown in Fig. 8.7. The reliability of each span has been assumed to be 0.99 i.e. a failure probability of 0.01. For all the paths, there is improvement in reliability with critical path protection. The reliabilities with SPP (shared *p*-cycle protection) are relatively lower for longer paths as compared to shorter paths. Whereas with

DPP (dedicated *p*-cycle protection), the longer paths can also be provided very high reliabilities. The reliability of one hop paths has also improved than that in SPP. Thus, in general, higher reliabilities can be provided irrespective of the length of the working path. The improvement in reliability is obtained at the cost of extra spare capacity required for critical traffic protection.

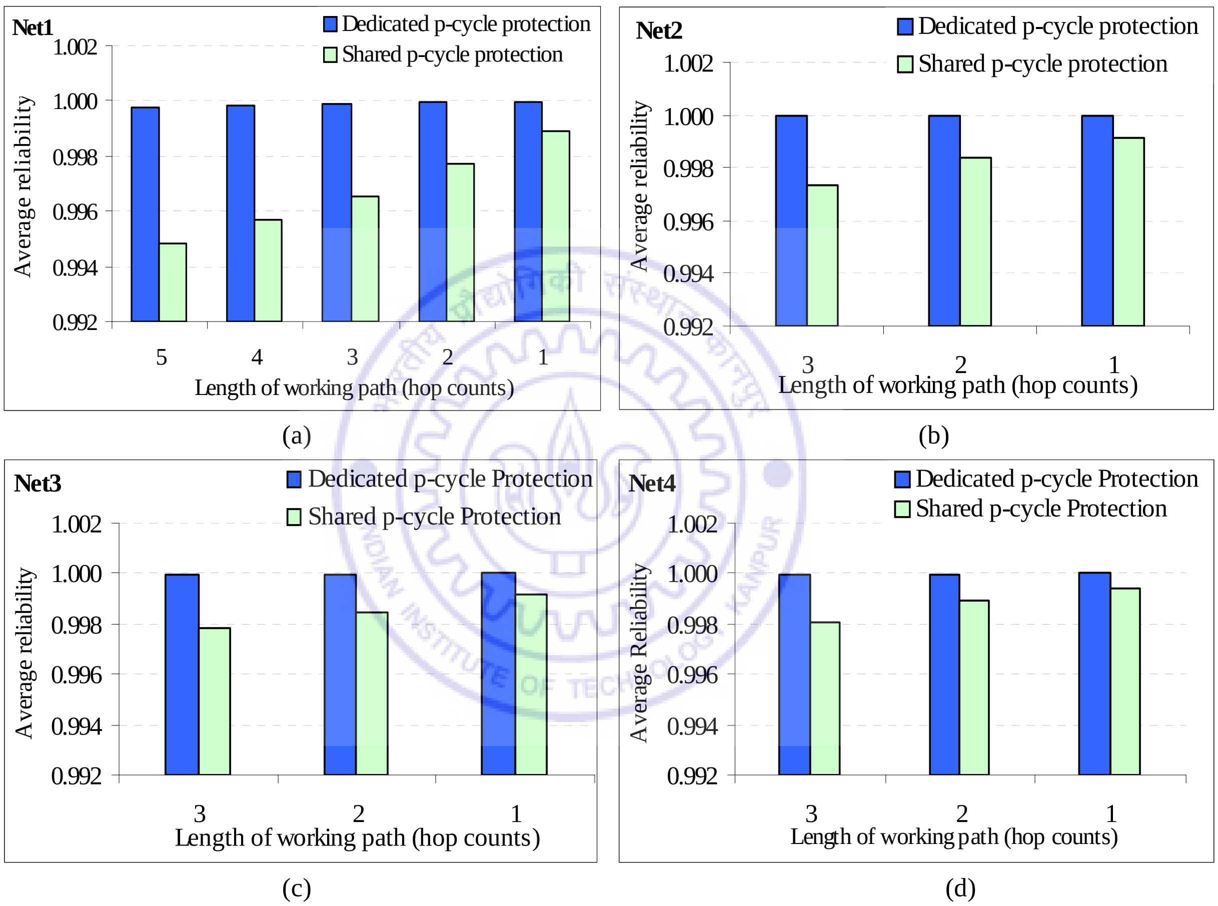


Figure 8-7 Improvement in reliability of critical traffic with dedicated *p*-cycle protection

8.5 SUMMARY

The specific requirements of network operators can be fulfilled with specialized protection techniques. With *p*-cycle based protection, it is better to remove a low availability span from the network to have, in general, better capacity efficiency.

The critical paths of the network can be provided guaranteed dual failure protection with small increase in overall spare capacity when the number of critical paths is small. This will provide very high values of reliability. However, if the number of critical paths is large then dual failure protection with RLBOPA will be more efficient. But the reliability, with dual failure protection with RLBOPA is going to be less as compared to critical path protection with dedicated *p*-cycles. This is obvious as critical path protection provides exclusive dual failure protection, while RLBOPA provides dual failure protection across the whole network. Due to above reason, network operators have to select appropriate model of protection for dual failure as per the customer's demand.

CHAPTER 9
CONCLUSIONS AND FUTURE WORK

In the field of optical network protection, *p*-cycles have outperformed other path and span based protection techniques, with their capacity efficiency and speed of restoration. Despite their better performance in terms of capacity efficiency and speed, certain issues still need attention. p-Cycles can be formed in any real network with DCPC protocol. The DCPC protocol finds one *p*-cycle in one iteration, and to find all the copies of the same *p*-cycle, the protocol has to run as many times as the number of copies of the *p*-cycle. Further, all the copies have to be deployed separately using separate switching fabrics at each node.

The other issue is the restored paths length which is the consequence of better capacity efficiency of *p*-cycles. The long lengths of the restored paths also reduce the reliability of the restored paths. Further, the allocation of *p*-cycles to the paths which are to be protected is also an important issue which has not been investigated in detail. We have, in the present work, studied and removed these shortcomings to improve the overall performance of *p*-cycle based protection, without compromising on any of the features of *p*-cycles. Further, a few methods for specialized protection techniques with *p*-cycles have been investigated.

The main contributions of the thesis are as follows.

- Study of DCPC with score and numpath metrics, and development of MDCPC to reduce the computational complexities and required number of switching fabrics, as well as reduction of switching complexities.

- Development of model for removal of loop-backs to reduce the restored path lengths without sacrificing the capacity efficiency or the speed of the *p*-cycles. The scheme has been evaluated with different methods of *p*-cycle formation, average nodal degree, number of nodes in the network, different traffic loads. Further dual failure survivability has also been evaluated
- Derivation of relationship between the average restored path lengths, before and after the RLB, and the number of nodes in the networks with average nodal degree of two.
- Development of distributed protocol for implementation of RLB in any real network protected with *p*-cycles along with the second phase reconfiguration of the restored path.
- Problem formulation of optimum *p*-cycle allocation to working paths and its solution with Hungarian algorithm such that the assignment of *p*-cycles to the paths through the failed span leads to minimum total restored path lengths.
- Development of reliability model for analysis of restored path with and without RLB.
- Investigations in protection provisioning techniques for low availability spans, and for the critical traffic through the network, with dedicated *p*-cycle protection. The main findings are given in the next section.

9.1 IMPORTANT FINDINGS

In chapter 5, DCPC protocol has been studied and modifications to improve the performance of DCPC have been investigated. In the DCPC protocol, both score and numpath metrics can be used for forwarding of statelets. A comparative study has been performed to find out the effects of the above two metrics on the protection capabilities of the formed *p*-cycles. For networks having average nodal degree $\leq$ 3.5, better protection capability is obtained with score metric, and for network of average nodal degree = 4.4, the numpath metric provides better results, with given spare capacities as required in link disjoint path protection. However, the differences are marginal. With spare capacities provided as per ILP, the performance of DCPC with score and numpath is almost similar. Hence, any of the two options can be used for the formation of *p*-cycles.

The computational complexities of the DCPC (distributed cycle pre-configuration), at optical layer, have been reduced with our MDCPC (modified DCPC) protocol. The MDCPC finds all the copies of a *p*-cycle in one iteration. Further, all the copies of a *p*-cycle can be configured simultaneously with the help of waveband switching by aggregation of all the copies. Now, the protection has been provided with coarser granularity at the waveband level. It reduces the number of *p*-cycles significantly. The requirement of switching fabrics has also been reduced considerably. The length of the statelet packet has been increased with a capacity field to achieve all the above features.

The mesh like efficiency of *p*-cycles is because of the shared protection provided to all the on-cycle and straddling spans. The disadvantage is very long restored paths; many times the length of the restored path is more than the number of nodes in the network, giving rise to loop backs. This shortcoming has been removed by our removal of loop back (RLB) algorithm described in Chapter 6. This algorithm has been developed to reduce the restored paths length with removal of loop backs without compromising on any features of the *p*-cycles. To retain the features such as speed of restoration of the *p*-cycles, RLB has been proposed as second phase reconfiguration of the restored path and distributed algorithm has been developed to implement the RLB in a real network and presented in Chapter 7. It has been found that reduction in the restored paths length also depends on the way, the allocation of the *p*-cycles is done to the paths of the failed span. Thus, to allocate the *p*-cycles to the paths of the failed span such that the total restored path lengths will be minimum, the OPA (optimum path allocation) problem has been formulated and solved with the help of Hungarian algorithm.

It has been verified with simulations that the average reduction in the restored path length is independent of the method of formation of *p*-cycles and traffic load; it depends upon the average nodal degree and the number of nodes in the network. The relationship between average restored path lengths and the number of nodes in the network have been derived for networks with average nodal degree 2.0 (ring topology) and verified through simulations. The maximum average reliability of the working paths is obtained with RLBOPA. The dual failure restoration has also been found to be more capacity efficient with RLBOPA.

Further, with analysis performed for protection provisioning for LAS (low availability spans), it has been found that better capacity efficiency will be obtained with removal of LAS from the network instead of providing dual failure protection to the traffic of the LAS. To provide guaranteed dual failure protection to the critical paths, use of dedicated *p*-cycles have been investigated along with *p*-cycles providing protection to non-critical paths and *p*-cycles with RLBOPA providing dual failure protection to all the traffic.

9.2 SCOPE FOR FUTURE WORK

Various problems still need to be investigated in the future. Some of these problems identified during the research work are as follows.

- The restored paths length can be reduced with RLB or RLBOPA only when there are loop backs in the restored path. If restored path is without loop back, then its length cannot be reduced with RLB or RLBOPA. In that case, the solution may be found with the help of hopcount limited model of *p*-cycle formation. By combining RLBOPA with *p*-cycles selected from hop-count limited model, guaranteed restored paths length can be provided to some specific paths. This work can be carried out in future to provide differentiated QoS to fulfill service level agreements with the customers.
- The paths can be established with protection satisfying the QoS requirements of reliability using LDPP or *p*-cycle based protection with RLBOPA or using dedicated *p*-cycle protection.
- The derivation of relationship for the average restored path lengths for networks having average nodal degree greater than two can be carried out.
- The RLBOPA can be used in the dynamic traffic environment to improve the blocking probability.
- In the specialized protection technique for Category I, we have found that for few spans the better capacity efficiency is obtained with case II. This can be further explored and some method for routing of primary paths can be devised such that even for these span one can have better capacity efficiency.

- The specialized protection techniques can be developed for spans having maximum amount of traffic such that during failure of these spans, the amount of unprotected traffic will not increase above a threshold value. The hop count limited *p*-cycles can be used for the purpose.
- We have observed that spare capacity for the formation of *p*-cycles for single failure protection, depends not only on the total amount of working capacity but also on the distribution of the working capacity. Some heuristics can be developed to select a working path from the group of all working paths having same hop counts.
- In the present work it has been assumed that network is fully convertible, future studies may be carried out with limited wavelength converters.
- The algorithms developed in this thesis may be used to design a network which could self organize itself such that optimum operating conditions will be maintained. The algorithms and protocols have to be developed such that network reconfigures itself periodically to achieve the optimum operating conditions dynamically.

9.3 OUTCOMES OF THE RESEARCH WORK

The work done during this research has resulted in journal papers, peer-reviewed conference papers, technical reports and development of Java-based simulation software. The research papers and technical reports published as outcome of this work are listed after the references.

In order to conduct the research work, a optical network simulation software was written in Java. The simulation software tool is used to form the *p*-cycles with DCPC and MDCPC. It has also been used to generate the input data files required for optimization software built using CPLEX. Many network survivability techniques are incorporated in the developed tool, like link-disjoint path protection, *p*-cycle based span protection with score and numpath metrics, dedicated *p*-cycle protection etc.. Dijkstra's algorithm with various metrics has been implemented. The removal of loop back and optimum *p*-cycle allocation using Hungarian algorithm have also been incorporated. The algorithms for testing and evaluating RLB and RLBOPA have also been implemented in the simulator. The dual failure restorability has also been implemented in developed software. The Java software also incorporates reliability calculations of the paths of the network.

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Appendix A

DCPC Protocol

3. Self-organization of the *p*-cycle state

Here we give an overview of the self-organizing strategy we have developed for the autonomous deployment and continual adaptation of the network cycle pre-configuration state. The Distributed Cycle Pre Configuration (DCPC) protocol is an adaptation of the statelet processing rules of the Self healing Network (SHN™) protocol [1, 2]. A statelet is embedded on each spare link and contains a number of state fields. Each logical link, as viewed by a node attached to it, has an incoming statelet and outgoing statelet. An incoming statelet arrives at a node on a link and originates from the adjacent node connected through the Link.

As in the SHN, each outgoing statelet has an incoming statelet which forms its precursor. An incoming statelet is a precursor to an outgoing statelet if the incoming statelet was cause, under the protocol rules, for the creation of the outgoing statelet. One incoming statelet can be the precursor for many outgoing statelets but each outgoing statelet can have only one precursor.

As a family of statelets is broadcast through a network, it forms a statelet broadcast tree which at each node in the tree, is rooted at the precursor port from which the outgoing statelet are propagated. The particular chain of causal events from the Sender through to the present node is called the statelet route.

There are only two node roles in the DCPC. A combined sender / chooser role called a "Cycler" and a Tandem node. The Cycler sources and later receives parts of the statelet broadcast pattern it initiates. Each node adopts this role in a round-robin fashion. While in this role it is temporarily in charge of the cycle-exploration process within the network as a whole. When not in the cycler role, each node plays a Tandem-node role which mediates the statelet broadcast, competition as in the SHN, but with a new decision criterion. At a high level of description, the DCPC first allows each node to explore the network for *p*-cycle candidates that are discoverable by it. After completion of its exploratory role as cycler (detailed below), it hands off to the next node in order by a simple "next-node hand-off" flood-notification. After all nodes have assumed the role of the cycler once, each "posts" its best found cycle in a distributed network-wide comparison of results. In this step all nodes hear the metric, and other details, of the globally best *p*-cycle candidate discovered by any of their peers. The competition flood expands through the network as each node locally re1ays the statelet with the best cycle metric, or asserts its own best if and while the latter is still superior to anything else it has received notice of yet. Eventually, the globa1ly best cycle candidate dominates everywhere. Upon thus learning of the winning candidate, the Cycler node who discovered this *p*-cycle, goes on to trigger its formation as a *p*-cycle. All nodes on the *p*-cycle update their local tables of restoration switching pre-plans to exploit the new *p*-cycle. The whole process then repeats, spontaneous1y, without any central control adding one *p*-cycle per iteration until a complete deployment of near-optimal *p*-cycles is built. Thereafter, it continually adapts the *p*-cycle set to changes in the working capacity layer.

A. Statelet Format

The DCPC statelet format has 5 main fields:

- *index*: Each state let belongs to an index family. Any outgo- ing statelet has an index value that is inherited from the incoming state let ~'hich is currently its precursor.
- *hopcount*: As a state let is relayed from node to node, a count of the number of ho s it has taken is maintained.
- *sendNode*: All statelet broadcast trees originate from only one node at a time. This is the current cycler node, which asserts its name in this field.
- *numpaths*: This is the accumulating figure of merit for prospective *p*-cycles that are represented within a statelet broadcast. It contains the apparent number of useful paths which the *p*-cycle candidate, contained in a given statelet, can pro- vide (details follow in this section.)
- *route*: This field contains the route, originating at the Cycler node, which a certain branch of a statelet broadcast tree represents between the Cycler and the current node.

B. The Tandem Node

The bulk of the processing in the DCPC algorithm takes place in the Tandem nodes. The Tandem node rules determines what *p*-cycle candidate the Cycler node will discover in a given round of global cyc1e comparison and formation. A Tandem node will broadcast each incoming statelet to the largest extent warranted by the statelets *numpaths* score within the context of the available outgoing link resources and other state1ets currently present. If an outgoing spare links on a span are occupied, a new incoming statelet can displace an outgoing statelet if it has a *numpaths* score better than the precursor with the lowest current score. Also, statelets on a given index can only be forwarded to adjacent nodes which are not already present in the accumulating route of the corresponding precursor. The single exception to this rule is that, a statelet may be broadcast from a Tandem to the Cyc1er node, which is present in all route fields. Figure 2 shows an example of this behavior, which limits the cycle exploration and formation process to consider only simple cyc1es. Additionally, at most one outgoing statelet of a given index may appear on a span. If

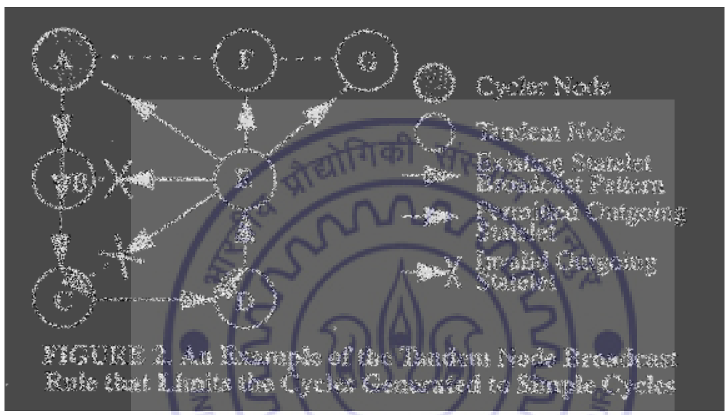

FIGURE 2. An Example of the Tandem Node Broadcast Rule that Limits the Cycles Generated to Simple Cycles

multiple incoming statelets, of like index, exist at a node, then the statelet with the best *numpaths* score becomes precursor for all outgoing statelets of that index. The emergent effect of these rules is that, shortly after triggering the process, with a sender primary flood, the Cycler receives incoming statelets whose route fields trace out cycles which begin and terminate at the Cycler node.

Now, we cover the Tandem node statelet competition rules. The idea is to identify the best prospective *p*-cycles. However, the Tandem node view is local only to the links directly connected to itself. Thus, a propagating metric of some type needs to be embedded and updated in each statelet so that the side effect of Tandem node competition is the generation of “good” *p*-cycle candidates. The metric or score that is used is intended to represent the potential of an incoming statelet’s route to form a *p*-cycle with a high ratio of useful paths to spare links consumed. The conundrum, however, is that the Tandem nodes must try to asses this metric before any complete cycle route has actually been formed.

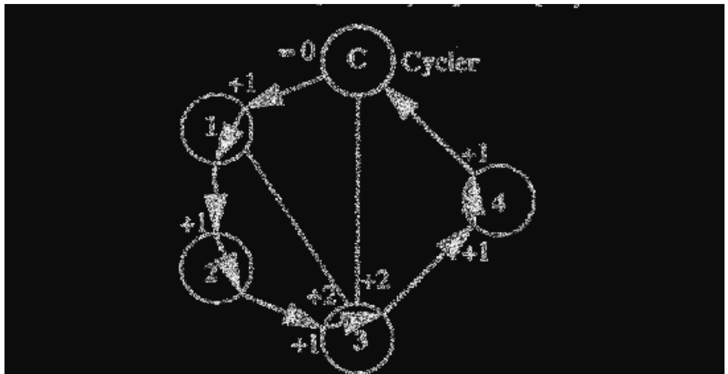

FIGURE 3. Evaluation of *numpaths* by the Tandem Node

To do this, the Tandem node rules operate on the presumption that any index-tree branch may eventually succeed in closing again with the Cycler, and evaluate it for useful paths on this basis. A statelet's score is s = (*numpaths*)/(*hopcount*) where *numpaths* is the number of useful paths that would be provided by a cycle formed from the union of the incoming statelet’s route and an imaginary direct span joining the tandem node to the cycler node. *Hopcount* is the number of spans so far traversed in the statelet's route. The number of useful paths, *numpaths*, is updated incrementally by each Tandem node as illustrated in Fig. 3. For each span on the route, *numpaths* is increased by *one*. *Numpaths* is increased by *two* for each node that appears in the route list and which the current Tandem node has a direct span connection, other than the span on which the current statelet has arrived. In other words for spans that would have a straddling relationship to the prospective *p*-cycle.

C. The Cycler Node Role

All statelet family broadcasts originate at the cycler node. To initiate the cycle-exploration process, the cycler places an outgoing statelet on one spare link in each span at its site. Each of these primary statelets has a unique index number. After the primary statelet broadcast, the cycler node invests a pre-determined time in sampling of the returning statelets. As returning statelets arrive, the cycler maintains a record of the received statelet (and statelet route) with the best score, *s*, as above. The Cycler persists in observing the incoming signatures because a cycle tends to provide a higher number useful paths as it is allowed to evolve under the collective interactions of the Tandem nodes. Usually it grows in size as it improves its score, until hopcount limiting effects stabilize the pattern of cycle-candidates formed. Fig. 4 is an illustration, from simulation, of how one prospective *p*-cycle evolves, usually outward, improving its score with time.

The sampling periods in our simulations are at most 1/3 of a second. But even if a few seconds was allowed for the best *p*-cycle candidates to emerge in a large network, there is little issue because the process is running in non-real-time. It is running in anticipation of a span failure, not in response to one, so there is no problem with investing this time to observe the evolution of the cycle metrics under the Tandem node actions. When the sampling time runs out, the cycler suspends all primary statelet broadcasts, terminates its role as the Cycler, and emits a Cycler hand-off flood (a statelet with op-code "hand-off" and the node name, on one link of each span.) The hand-off flood is relayed (once only by all nodes, without link persistence, with one copy in each span). When node *n* hears "hand-off flood, *n-1"* it knows that it is its turn to become cycler.

D. Construction of the Best Candidate p-Cycle

After a complete round of cyc1er action by every node, the last node in the sequence (i.e., when *n* equals the number of network nodes) knows all nodes have assumed the role of the cycler and are ready to take part in a network wide comparison of results. The purpose is to find the one globally best *p*-cycle candidate found by any cycler node. This is done automatically by initiation of a global comparison flood by the last node in the sequence of cycler exploratory phases. The initiating node broadcasts a single statelet, containing the node's name and its best cycle’s score, on each span. When adjacent nodes receive such a statelet they compare the received best score to their local best score and relay the better of the two into all spans, along with the name of the node who is reporting the better cycle. If scores are equal, precedence is based on ordinal rank of the node names involved. Rapidly, only the single best score is present everywhere, and the node which found this candidate will proceed to initiate its construction.

To deploy the *p*-cycle that has emerged from the all-nodes comparison of results, the node associated with the winning candidate cycle examines the route field of that cycle and identifies the node adjacent to itself which appears first in the route vector. It then finds a spare link on the span to that node and places a statelet with a “construct-cycle” op-code, followed by the route vector. The adjacent node makes a cross-connection between the incoming spare link bearing this statelet, and a spare link in the direct span going to the next node in the route vector. It then forwards the cycle-constructing statelet on that spare link; subsequent nodes effect a similar connection and relay the construction command in a similar manner. As each node along the route makes its cycle-constructing cross-connection., it also updates its local list of uncovered working links, and notes all of the working links for which the current *p*-cycle can be used for restoration (i.e.. any working link from this site to any of the other nodes listed in the route vector). These considerations ready the node to use the *p*-cycle immediately for restoration. They also are reflected in subsequent cycle-exploring iterations so that future *numpaths* measured are scored accurately, given the reduction in uncovered working capacity that each constructed *p*-cycle creates.

When the sequence of relays that constructs the *p*-cycle returns to the initiating Cycler node, that node makes a final cross-connection to the first spare link on which it began the cycle-building process, completing the *p*-cycle. Once deployed, any node on the *p*-cycle may use the cycle for restoration. The only further special role for the custodial node for this cycle is to apply and maintain a statelet into it that repeats the route vector. The *p*-cycle is thus put into storage with a holding statelet on it that support continual self-checking of the continuity and correctness of the cycle route while in storage by the nodes on it. To use any *p*-cycle for restoration, any node on the cycle must only first test for in-use status (marked on the holding statelet), assert its own in-use indication (assuming its free), and bi-directionally substitute the affected signal to go on this *p*-cycle. Thus, the real time restoration procedure, once *p*-cycles are in place, reduces to being identical in this regard to the SONET BLSR standard.

Appendix B

Average Restored Path Length for Ring Topology Networks

Let us consider the $\bar{d}$ =2 network (Fig. B.1). Let the total number of nodes in the network be n. The working paths shown by dotted lines (Fig. B.1) are shortest paths based on hop count, for unit traffic matrix. There will be two cases, corresponding to n odd, and n even. If n is even, then there will be two paths, each with hop counts H, where H is from 1 to $n/2-1$, and one path with hop count $n/2$. For odd n, there will be two paths, each with hop counts H, where H is from 1 to $(n-1)/2$. The length of the *p*-cycle path, protecting working paths, will be $n-1$. Hence, the restored path length without RLB (shown by dashed line)

L_{FP}= $n-1+H-1$

$=n+H-2$.

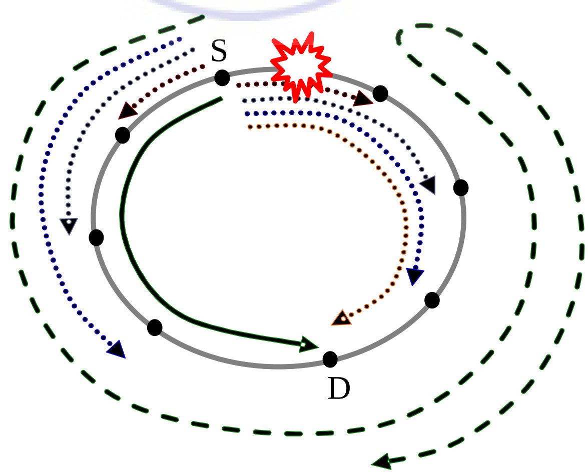

Figure B.1. Working paths (dotted lines), restored path without RLB (dashed line), restored path with RLB (thick line)

The restored path length with RLB

$L_{FR} = n - H$.

For all the paths originating from a node, when n is even,

$$\sum_{\forall i \in S, \forall r \in W_i} (L_{FP})_{r,i} = \left[\sum_{H=1}^{H=\frac{n}{2}-1} 2\{H(n+H-2)\} \right] + \frac{n}{2}\left(\frac{3n-4}{2}\right)$$

$$= \frac{n}{6}(n-1)(2n-1) . \qquad \text{(B.1)}$$

Here, left hand side is the sum of lengths of the restored paths, over all the spans if they fail (one at a time) and for all the paths passing through that span. In the right hand side, the order of summation has been changed, and total number of spans in a path is summed over all the paths. Similarly,

$$\sum_{\forall i \in S, \forall r \in W_i} r_i = \left(\sum_{H=1}^{H=\frac{n}{2}-1} 2H \right) + \frac{n}{2}$$

$$= \frac{n^2}{4} . \qquad \text{(B.2)}$$

$$\sum_{\forall i \in S, \forall r \in W_i} (L_{FR})_{r,i} = \left[\sum_{H=1}^{H=\frac{n}{2}-1} 2\{H(n-H)\} \right] + \frac{n^2}{4}$$

$$= \frac{n}{6}(n^2-1) . \qquad \text{(B.3)}$$

Hence, from Equations (6.1) and (6.2) (section 6.4),

$$L_{WRLB} = \frac{2(n-1)(2n-1)}{3n}; \qquad \text{without RLB,} \qquad \text{(B.4)}$$

and

$$L_{RLB} = \frac{2(n^2-1)}{3n}; \qquad \text{with RLB.} \qquad \text{(B.5)}$$

Similarly, when n is odd,

$$L_{WRLB} = \frac{2(2n-3)}{3}; \qquad \text{without RLB,} \qquad \text{(B.6)}$$

and

$$L_{RLB} = \frac{2n}{3}. \qquad \text{with RLB.} \qquad \text{(B.7)}$$

List of Publications

- ***Journal Papers***

[A1] Rachna Asthana, Y.N. Singh, “Distributed Protocol for Removal of Loop Backs and Optimum Allocation of p-Cycles to Minimize the Restored Path Lengths,” *IEEE J of Lightwave Technology*, vol. 26, no. 5, pp. 616-628, March 2008.

[A2] Rachna Asthana, Y.N. Singh, “Second Phase Reconfiguration of Restored Path for Removal of Loop Back in P-Cycle Protection” *IEEE Communication Letters*, vol. 11, no. 2, pp. 201 – 203, Feb 2007.

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- ***Peer-Reviewed Conference Papers***

[B1] Rachna Asthana, Y.N. Singh, “Removal of Loop Back in *p*-cycle Protection: Second Phase Reconfiguration” in *Proc. of 10th IEEE International conference on Communication Systems (IEEE ICCS 2006)*, held at Singapore, during Oct 30, to Nov 1, 2006,.

[B2] Rachna Asthana, Y.N. Singh, “Reliability Improvement with Critical Span Protection using Modified Algorithm of Pre-configured (P) Cycles”, in the *Proc. of International Conference on Optics and Optoelectronics ICOL 2005* held at Dehradun during Dec 12, to Dec 15, 2005.

[B3] Rachna Asthana, Taru Garg, Y.N. Singh, "Critical Span Protection with Pre-configured (P) Cycles" in the *Proc. of International conference Photonics 2004* held at Cochin during Dec 9, to Dec 11, 2004.

[B4] Rachna Asthana, Y.N. Singh, "Survivability in all Optical Networks", in the *International Conference on Optical Communication and Networks 2003 (ICOCN 2003)* held at Bangalore during Oct 20, to Oct 22, 2003.

- ***TECHNICAL REPORTS***

[C1] R. Asthana, "A distributed protocol for second phase reconfiguration and *p*-cycle allocation to minimize the restored path lengths in *p*-cycle protected networks," *ACES/EE Departmental Library*, IIT Kanpur, Tech. Rep. 2007/2295/TR, July 2007.

[C2] R. Asthana, "Second phase reconfiguration of restored path for removal of loop back in *p*-cycle based protection in optical networks," *ACES/EE Departmental Library*, IIT Kanpur, Tech. Rep. 2006/2294/TR, March 2006.