Improving Double Link Failure Tolerance in Optical Networks using p-Cycles

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CERTIFICATE

It is certified that the work contained in the thesis entitled " **Improving Double Link Failure Tolerance in Optical Networks using p-Cycles**" being submitted by **Pallavi Athe** has been carried out under my supervision. In my opinion, the thesis has reached the standard fulfilling the requirement of regulation of the Ph.D. degree. The results embodied in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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Synopsis

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Optical networks are high speed networks, built using fiber optic communication systems and dense wave division multiplexing(DWDM) technology and are capable of using huge bandwidth available in optical fiber. Optical network forms the major part of Internet backbone and carries enormous information. A link or node failure even for a few minutes can cause huge loss of data and hence the revenue. After such failure, the ability of network to maintain service is known as its survivability. Designing a survivable optical network having fast recovery from failures with least possible redundant resources has been an area of extensive research. Single link failure has been explored extensively. Double link failure protection has also gained interest due to significant probability of two simultaneous link failures. The double link protection optimization problem has higher complexity, since large numbers of variables are involved as compared to the single link protection.

One of the efficient option for achieving double link survivability could be use of pre-

configured cycles (p-cycles). They provide the speed of ring protection and capacity efficiency of mesh based protection schemes. In this work we have proposed three different p-cycle based protection methods to protect an optical network from two-link failures. We have also proposed the concept of impact zone which quantifies the loss of protection in a network after first link failure and used it to improve the double link failure protection of the optical network.

The work has been organized in chapters 1 through 6 in the present thesis.

Chapter 1 describes the evolution of present telecommunication networks. A brief description of optical networks and technology advancements in them from first through the fifth generation have been described in this chapter. Architectures of communication networks based on geography and technology have been presented, which illustrate the place and importance of optical networks in the communication network.

In Chapter 2, various survivability schemes for optical networks have been reviewed. P-cycles is the most promising method of link protection due to high recovery speed as well as spare capacity efficiency. Different kinds of protections which can be provided by p-cycles have been described in this chapter. Various methods to form and implement p-cycles in optical networks are also described in this chapter. Multiple failure scenarios in the network with the importance of double link protection have also been studied. Chapter 2 also presents a brief literature review on double link failure survivability techniques.

Improved double cycle method (IDB) which is an improvement over double cycle method has been introduced in **Chapter 3**. DB and IDB methods use a pair of p-cycles for each link to protect the optical network from two link failures. In IDB method priority is assigned to each p-cycle within the pairs to protect the link. The strategy of assigning priorities among the p-cycles of the pair reduces the number of variables and constraints which are required to formulate the integer linear program (ILP) of IDB.

Thus, the number of variables and constraints becomes much less than what is needed in DB method. We observed that the spare capacity efficiency and time required to solve the ILP reduces for IDB method.

In Chapter 4 link pair method (LPM) and Single p-cycle (SG) method for double link protection have been introduced. In the LPM all the possible pairs of links in the optical network are considered, and p-cycles are selected from the non-intersecting set of cycles for each pair of links. We also observed that LPM requires less computational resources as compared to both DB and IDB method. Single p-cycle (SG) method, which uses one p-cycle to protect a link from two simultaneous link failures, is also introduced in this thesis. SG method is also able to compute the spare capacity of large networks for which DB method fails, because number of variables required for the SG method is $O(L.P)$ while DB method requires $O(L.P^2)$ variables (where L and P represents the number of links and the number of cycles respectively for a given network). Also, ILP of the SG method is simpler than for any other two-link failure protection method. Consequently, the time required in the ILP formulation and ILP solution is significantly less.

An optical network designed for single link failure also has some inherent double link failure survivability. **In Chapter 5**, we have defined impact zone which mathematically represents the effect of the link failure on the network protection capacity. Various methods are then proposed and analyzed to reduce the impact zone, which leads to increase in double link failure survivability of the network.

Finally, conclusion, future scope and contributions of the present thesis is given in **Chapter 6**.

Dedicated to

My Family

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Biggest thanks to my family for their incredible love and support. They are the reason I have come so far.

(Pallavi Athe)

List of Symbols

$G(N, L)$	Bidirectional graph with N number of nodes and L number of links.
$< k >$	Average node degree.
S	Set of spans, indexed by i.
P	Set of cycles, indexed by p.
c_i	Cost of unit capacity of link i.
n_p	Number of unit capacity copies of p-cycle p.
$n_{i,p}$	Number of unit capacity copies of p-cycle p required to protect link i.
SE	Spare capacity efficiency.
w_i	Working capacity on link i.
Q_i	Set of protection-pairs of link i, indexed as $(p, q)_i$.

List of Abbreviations

ARPANET	Advanced Research Projects Agency Network
APS	Automatic Protection Switching
BLSR	Bidirectional line Switched ring
CDC	Cycle Double Covers
DARPA	U.S. Defense Advanced Research Project Agency
DB	Double Cycle Method
DCF	Dispersion Compensated Fiber
DWDM	Dense Wavelength division Multiplexing
EON	Elastic Optical Network
FIPP	Failure Independent Path Protecting p-cycles
FIPP	Failure Independent Path Protecting p-cycles
HOS	Hybrid Optical Switching
IDB	Improved Double Cycle Method
ILP	Integer Linear Program
IP	Internet Protocol
IZ	Impact Zone
LPM	Link Pair Method
NEPC	Node Encircling P-cycles
NFV	Network Function Virtualization
NWC	Non-restored Working Capacity
Och DPRing	Optical Channel Dedicated Protection Ring
ODU	Optical Data Unit
OMS-SPRing	Optical Multiplex Section-Shared Protection Ring
OTN	Optical Transport network
OXC	optical cross Connect
P-cycle	Pre-configured cycle
PDH	Plesionchronous Digital Hierarchy
PSTN	Public Switched Telephone Network
PWCE	Protection Working Capacity Envelope optimization
R	Restorability
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SDH	Synchronous Digital Hierarchy
SDN	Software Defined network
SG	Single P-cycle Method
SPU	Service Path Unavailability
SRLG	Shared Risk Link Group
SONET	Synchronous Optical Network
TCP	Transmission Control Protocol
WDM	Wavelength division Multiplexing

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Chapter 1

Introduction

Communication is the ability of human beings to exchange experience, knowledge and information among each other. Exchange of information and knowledge has led to the development of society. The mode and extent of communication is changing ever since the dawn of mankind. Higher the speed and extent of communication, greater will be the rate of development. Therefore, mode of communication played a significant role in the development of mankind.

Early communication began with the smoke and drum signals. The first fixed semaphore appeared in Europe in 1790's, and remained until 1830's when electrical telecommunication started to emerge. Invention of Morse telegraph [1] system in 1840 marked the start of modern telecommunication system. Telegraph communication expanded to the global level influencing daily lives, businesses, and government affairs.

The success of telegraph and growth in electrical manufacturing industry gave background for the telephone. Alexander Graham Bell received a patent for his invention of the telephone in 1876 [2]. Initially, telephone communication was restricted to a distance of around 100 miles due to use of iron wires. The stepping switch invented by Almon Brown Strowger [3] in 1891 led to the automation of telephone switches. Coaxial

cable was invented in 1936, and it rendered high bandwidth to transmit thousands of telephone calls or video signal over longer distances.

The shift from analog to digital marks a tremendous change in telecommunications. Digital communication provided infrastructure for transmitting not only voice but anything which can be translated to numbers. Digital switches allowed more flexible design and operation of the networks.

Later, Internet was formed as a global network of computers. The computers are connected to each other via PSTN(public switched telephone network) to form academic, research and commercial computing network. Backbone of the Internet is a set of paths which provides long distance communication among regional networks. The Advanced Research Projects Agency Network (ARPANET) funded by the U.S. Defense Advanced Research Projects Agency (DARPA) was the first prototype of the Internet. The research funded by DARPA developed two protocol suits-Transmission Control Protocol (TCP) and Internet Protocol (IP), which are used for transmission of information among different kinds of systems.

The present telecommunication network technology is based on optical transmission system. Optical fiber offers advantages of higher bandwidth, low power loss allowing long-distance transmission, along with the immunity to electromagnetic interference, and secure transmission of information and is light in weight. Optical networks are briefly explained in the section below.

1.1 Optical Network

Today, almost every part of the world is connected via the Internet. Optical network constitutes the backbone of the Internet. The optical network is an interconnection

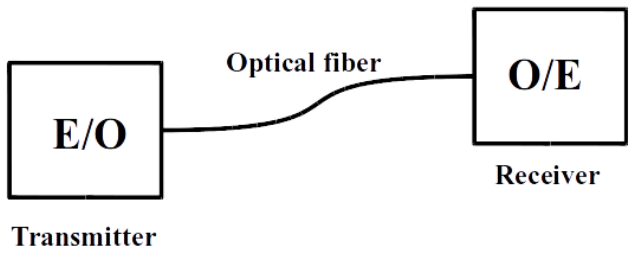


Figure 1.1: A fiber optic system

of nodes equipped with optical systems through a medium of optical fibers. These interconnected nodes are capable of multiplexing and demultiplexing information in the optical domain and transmitting and receiving them over optical fiber.

1.1.1 Fiber Optic System

A fiber optic system consists of an optical transmitter (E/O), optical fiber and Optical receiver (O/E) as shown in Fig. 1.1. An optical transmitter consists of an optical source, such as a Laser or an LED, and signal conditioning electronics which converts the electrical signal into optical domain and feeds it to the optical fiber. The optical signal is guided through the optical fiber to the optical receiver. The O/E receiver converts the optical signal to electrical signal using a photodiode and electronic circuitry.

Communication through an optical fiber is usually explained by the phenomenon of total internal reflection to guide the optical signal inside the optical fiber. In 1854 John Tyndall [4] first demonstrated that light could be guided through a curved stream of

water using the phenomenon of total internal reflection. Optical fibers were used only for optical imaging in the biomedical field till 1960. The development of laser technology renewed the interest in this field of fiber optics. The first laser was constructed by T. H. Maiman [5] [6] at Hughes Research Laboratories in 1960. It was based on theoretical work of Charles Hard Townes and Arthur Leonard Schawlow. The first semiconductor injection laser was invented by Robert N. Hall [7] in 1962, a device now used in all compact disk players, laser printers, and most optical fiber communications systems.
In 1966, Charles K. Kao, working at Standard Telecommunication Laboratories in Harlow theoretically and experimentally showed the possibility of using optical fiber as a high capacity and long-distance transmission medium for telecommunications [8]. Optical fibers had extremely high attenuation (1000 dB/Km) which restricted there use as a medium for communication. After the invention of low loss optical fiber (20 dB/Km) by Corning, there use in the communication became possible.

1.1.2 Generations of Optical Network

The advancement in the semiconductor industry and fiber optics led to the development of high-speed optical network based on fiber optic systems. Fig. 1.2 illustrates the evolution of optical network from first to the fifth generation. The first generation of optical network started from 1970 and introduced PDH (plesiochronous digital hierarchy) for point to point (p-t-p) fiber optic system for long haul telecommunication networks. Networking was not enabled in the optical domain since only one optical channel could be transmitted through an optical fiber in the first generation of optical network. Networking was performed in electrical domain using time division multiplexing.

In the second generation of optical network, PDH was replaced by synchronous hier-

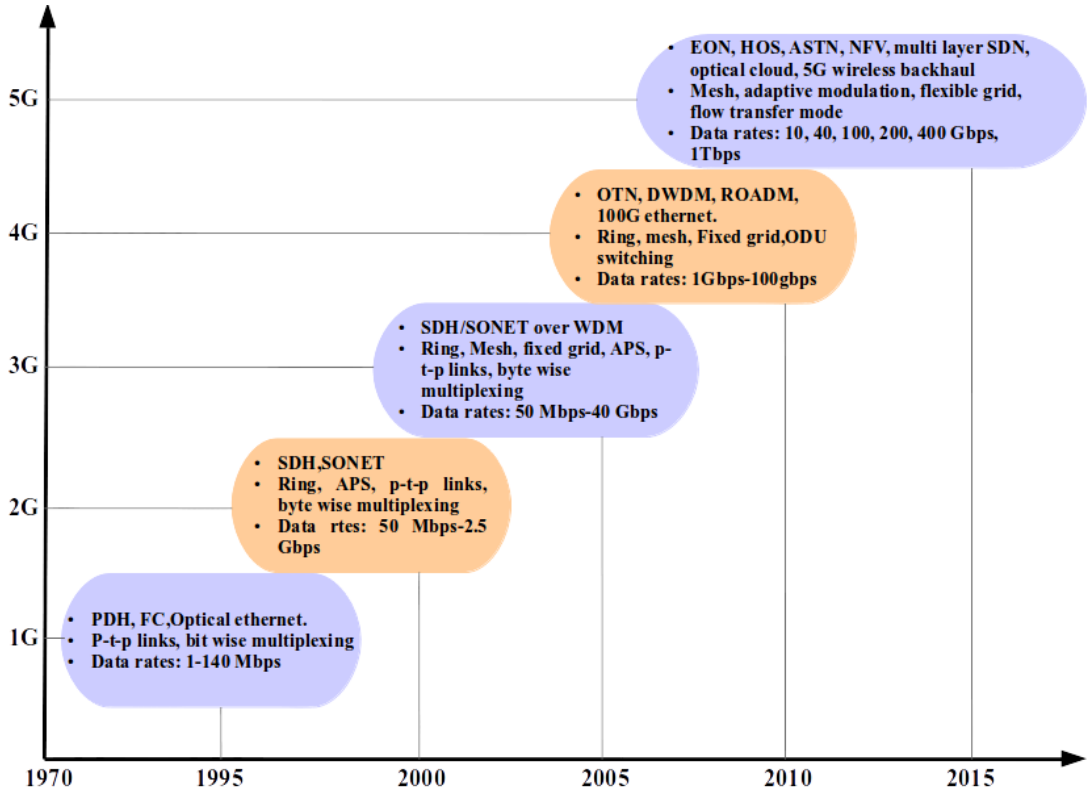


Figure 1.2: The evolution path of optical network: PDH: Plesiochronous Digital Hierarchy, SDH: Synchronous Digital Hierarchy, FC: Fiber Channel, SONET: Synchronous Optical Network, APS: Automatic Protection Switching, EON: Elastic Optical Network, ASON: Automatically Switched Optical Network, HOS: Hybrid Optical Switching, OTN: Optical Transport Network, ROADM; Reconfigurable Optical Add/Drop Multiplexer, SDN: Software-Defined Networking, NFV: Network Function Virtualization (adapted from [9])

archy scheme for multiplexing. A number of multiplexed voice channels with 64Kbps bit rates can be put together in synchronous hierarchy format to transmit over optical channel. This synchronous hierarchy is commonly known as synchronous optical networking (SONET) in the United States and Canada, and and synchronous digital hierarchy(SDH) in the rest of the world. To handle data transmission, protocols such as Ethernet and ATM(asynchronous transfer mode) were introduced. These protocols were implemented over higher layers and were not directly connected with the optical channels.

Increasing the SONET/SDH bit rates was not enough to satisfy the growing bandwidth requirements of the network. In the third generation of optical network, several new technologies were developed which enhanced the transmission rates without the use of repeater and regenerators over longer distances. Wavelength division multiplexing (WDM) enabled multiplexing of a number of optical signals on single fiber. The principle of stimulated emission was used in an optical amplifier to amplify the optical signal without optoelectronic conversion to increase the repeater-less transmission distances further. Also, now the effect of dispersion could be compensated by periodically deploying dispersion compensated fibers (DCF) allowing longer spans. The deployment of optical amplifier and DCF along the optical fiber enabled transmission of optical signal up-to 1000 Kms without the use of optoelectronic regenerators. The distance was gradually increased, and transoceanic transmission was made possible without the use of optoelectronic regeneration. In a WDM system, each multiplexed wavelength could be a different kind of digital signal and could follow distinct optical path enabled through optical switching. Add-drop multiplexing or cross connection of optical signals were performed using an optical add-drop multiplexer (OADM), and an optical cross connect (OXC).

Dense wavelength division multiplexing (DWDM) was introduced in the fourth gen-

eration of optical network. In a DWDM system, WDM channels are densely packed to utilize bandwidth more efficiently. Reconfigurable optical add drop multiplexers (ROADM) improved networking by enabling dynamic assignment of the light path for provisioning and restoration purposes in an optical network. Optical telecommunication network (OTN) standards were developed in the late 1990s and early 2000s [10]. OTN [10] was standardized to add operations, administration, maintenance, and provisioning (OAMP) functionality at the optical level such as DWDM. OTN defines frame structure known as "digital wrapper" to encapsulate data frame of any native protocol, to create an optical data unit (ODU), similar to SONET/SDH. Multiple data frames can be wrapped together into a single entity with comparatively less management overhead in a multi-wavelength system. To provide higher-speed Ethernet, 40GbE and 100GbE, a significantly revised standard ITU-T G.709, was approved in December 2009 [11]. OTN is a very efficient packet transport network due to its ability to provide a transparent mapping of client data and timing and optimal container sizes for Ethernet.

The fifth generation optical networks requires enhancement in data rates by improving bandwidth utilization along with fast and efficient provisioning of optical path. This can be achieved by utilizing advanced optical components capable of providing software controlled optical path and flexible bandwidth. Advanced networking concepts like Elastic Optical Network (EON) and Hybrid Optical Switching (HOS) can also be used to enhance flexibility and efficient utilization of the optical network. Standardizing and implementing the software defined network(SDN) in optical domain and use of high speed optical interconnects for data center are further expected to enhance the performance of communication networks.

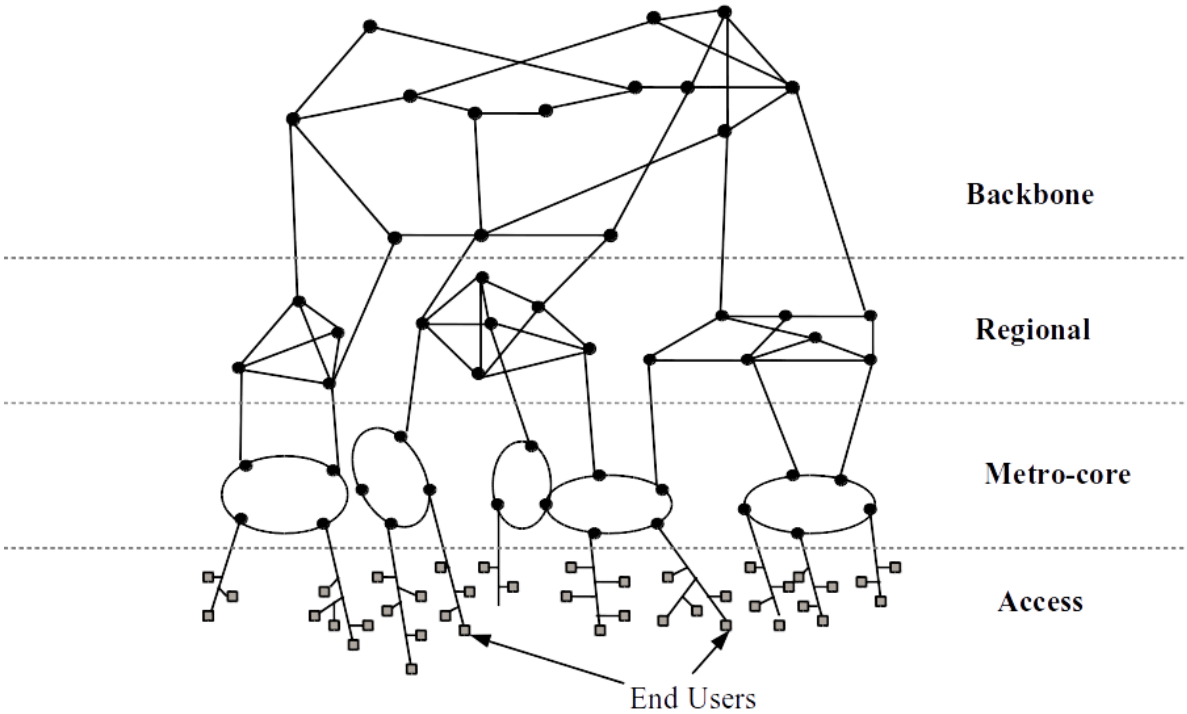


Figure 1.3: Geographical hierarchy of telecommunication network. (Adapted from [12])

1.1.3 Geographical Hierarchical Architecture of Communication Network

Based on the number of users, required capacity and geographical range, networks can be segmented into four tiers as shown in Fig.1.3. The access network is closest to the end users, ranging from individual Internet users to corporate offices. Access network spans few kilometers of area covering tens to hundreds of individual users. Various media and technologies may be used to implement access network ranging from copper wire, wireless and optical fibers. Transmission rates in the access network vary, depending on users requirement, applications, and technology implementation.

A metro-core networks aggregate the data traffic from the access networks. A metro-core network connects thousands of customers and spans ten to hundreds of kilometers.

Metro-core network support many types of services from voice, leased lines for transport, and application services from data centers, like data storage, video, etc., and distributed applications mostly peer-to-peer to systems. Metro-core networks incorporate synchronous and asynchronous transmission equipment and cater to users with varying bandwidth demands.

A regional network receives and provides traffic to and from multiple metro networks. A regional network covers thousands of users and spans hundred to thousands of kilometers of area. Regional traffic is interconnected via the backbone network.

Backbone network covers millions of users covering thousands of kilometers of geographical area. Backbone network carries traffic speeds of Tera-bits per second (Tbps) to Peta-bits per second (Pbps) in aggregation over optical fiber using mostly DWDM technology. Backbone networks employ optical cross connects, optical add drop multiplexers and photonic switches to direct traffic within the network.

New technologies are generally deployed in the backbone network first, as it carries a large amount of traffic and affects lager network area. As the technology matures and becomes cost efficient, technologies are employed even in lower tiers of the network. Even though same technology prevails in different tiers of network, but implementation may differ. For example, backbones use sophisticated optical transmitters and receivers to accommodate larger number of wavelength on a single fiber as compared to a regional and metro-core network. Access network uses a passive optical network(PON) to connect end users who do not use large amount of bandwidth all the time.

1.1.4 Technology Based Layered Architecture of Network

A communication network can be viewed as layers providing functionalities driven by specific technology such as IP network, SDH network, and Optical network. Group

of service sub-networks constitutes a service layer network. Service sub-networks can have client/server or peer to peer relationship. Cellular network, PSTN and Signalling System No.7(SS7) are examples of service sub-networks. Fig. 1.4 shows the technology specific architecture of telecommunication network. A service network can be supported by Optical transport network, SDH transport network, ATM transport network, and IP transport network.

The nature of the relationship among the network layers forming a vertical association is important, as it indicates that client layer service is carried by server layer network. Fig. 1.4 shows/illustrates the relationship between various network layers. A server layer network may have more than one client layer network. For example, SDH network may bear IP as well as ATM network, and SDH can be supported by optical network.

The need for fast path provisioning with high availability and low latency has led the research towards software defined network(SDN), and network functions virtualization(NFV) which can provide paths dynamically [13], [14], [15]. In the present scenario, network layers are controlled individually and to create an end-to-end path, operators set up path manually for each network layer. Integrated control over multi-layer and a multi-domain network can facilitate dynamic provisioning of end-to-end paths [16].

1.2 Organization of Thesis

This thesis is organized as follows. Chapter 2 is a review of survivability schemes in an optical network. Importance of multiple failure survivability in an optical network is discussed with an emphasis on two link failure survivability.

In Chapter 3, two link survivability method (double cycle method) has been described which use two link-disjoint p-cycles to protect a link. A further improved version of the

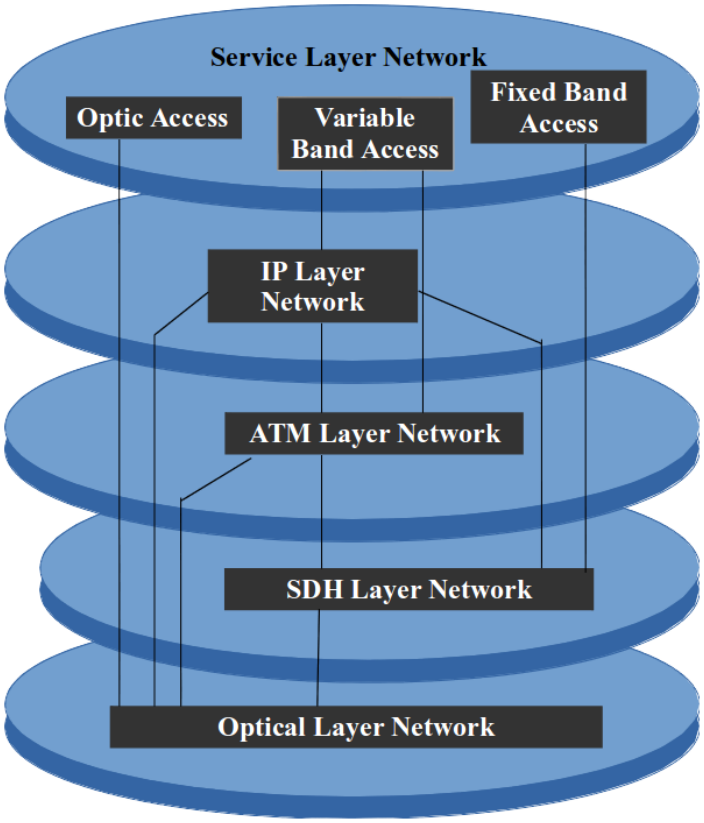


Figure 1.4: Technology specific architecture of telecommunication network.

method has been introduced. Integer linear program for double cycle method and its improved version has been formulated.

In Chapter 4, we have proposed two methods; link pair method (LPM) and single cycle (SG) method using p-cycles to protect an optical network against two link failures. In LPM each pair of the link uses non intersecting p-cycles for the protection from simultaneous failure. In single cycle method, a working capacity on a link is protected from the two simultaneous link failures using only one p-cycle. ILP has been formulated for LPM and SG method. The number of variables and constraint for LPM is less as compared to DB and IDB method. There is a further reduction in the number of variables and constraints for single cycle method as compared to LPM method. The time required to formulate and solve ILP in LPM is less compared to DB and IDB method. SG method has the least complexity for ILP formulation and solving it.

In Chapter 5 Double fault tolerance of a network protected for 100% single link failure has been investigated using a new parameter impact zone. Impact zone is formulated for the links in a network protected by single link failure. Additional constraints are added to single link protection ILP to reduce the impact zone to improve double link protection of the optical network. By using suitable constraints, the impact can be reduced to zero, thereby achieving double fault tolerance. We have observed that there is a trade-off between spare capacity efficiency and impact zone. We have shown how limiting constraint can be used to tune a specific spare capacity and impact zone.

The last chapter of the thesis, Chapter 6 concludes the entire work. Some future problems which are worth investigating related to this work have also been suggested in this chapter.

Chapter 2

Survivability in Optical Networks

Almost every aspect of modern society depends on information networks. Unavailability of network services can have impact on public facilities, business trustworthiness, and national security. Path in a network is usually connected via various links and nodes each of which may fail causing disruption. Therefore a resilient network is desirable which requires redundant resources. This capability to survive failures by using redundant resources is known as network survivability. Pre-planning is required for hassle free working of the network along with efficient utilization of the redundant resources for survivability.

Generally, it would be beneficial to protect different layers depending on the nature and location of faults. Higher network layers provide a protection mechanism for a smaller amount of traffic handled by each instance independently. Giving protection only at higher layers will be slower if the failure is in the physical layer which carries an enormous amount of data. It is because different higher layer instances will handle the different flows at different nodes. Furthermore, as the endpoint transport layer entities are involved, the restoration will be slower. Survivability of backbone network which broadly consists of optical fiber systems and carries a huge amount of information in a

very short duration is essential. Currently, we expect any traffic restoration to happen in less than 50m sec, which is the benchmark provided by synchronous digital hierarchy (SDH) systems. To ensure quick recovery of faults, distributed protection is preferred. Failure may arise due to link or node failure. Link failures are more frequent and mostly arise due to fiber cuts. Optical fibers laid underground get damaged due to excavation (dig-ups), craft/workmen error, rodents, flood, and extreme temperature [13]. The entire station which acts as a node in a network can fail due to catastrophic events such as earthquakes and floods causing failure of all the traffic flowing in/out or through the station. Individual channel failure can also occur due to the failure of active components such as transmitters and receivers. For active components protection, generally redundant resources need to be provisioned.

Various protection schemes are feasible for optical networks. They differ from each other in terms of speed of recovery, amount of redundant capacity required, the possible number of simultaneous fault recovery and complexity of operation. Protection schemes are also provided according to the requirement and on demand. In the following subsection, we have described various protection schemes proposed or used for optical networks.

2.1 Dedicated and Shared Protection

Protection schemes can be categorized as dedicated or shared protection. In dedicated protection, dedicated routes are individually assigned for each working connection. In case of failure of working connection, traffic is automatically switched on to the designated dedicated protection. Two types of schemes can be used in dedicated protection: 1+1 and 1:1 protection. In 1+1 protection, traffic is transmitted on two fibers simultaneously, and at the receiver end, one of the two signals is selected. If one of the fiber

fails, the signal from the intact fiber is selected at the receiver. In 1:1 protection, in normal conditions the traffic is transmitted over working fiber while the protection fiber remains idle or can be used to carry low priority traffic. In case of failure of working fiber, traffic is rerouted through the protection fiber after preempting the low priority traffic. 1+1 protection is faster than 1:1 protection scheme since 1:1 protection requires signaling for switching the traffic over to the protection capacity.

Shared protection utilizes the fact that all working paths do not fail concurrently. A network is designed to share protection capacity among multiple working paths, significantly reducing the required spare resources. Shared protection gives better efficiency in the use of spare resources, but this may lead to contention in case of multiple simultaneous failures. Therefore, network needs to be carefully designed to meet the survivability requirement with least resources.

2.1.1 Link Protection, Path Protection and Path Segment Protection

Protection schemes can also be categorized as a) link and b) path protection. In a link protection scheme, protection route is provided between the end nodes of the link to be protected. In case of link failure, switching takes place at the end nodes of the failed link. Fig. 2.1 shows a working path (a-b-c-d-e-f) with link protection. As an example, if link (c-d) fails then traffic on link c-d is routed through (c-l-m-d). Link protection is also fault dependent since protection route depends on the failed link. Path protection scheme provides protection between the end nodes of the working path. Working traffic is rerouted on to the protection path in case of any failure on the working path. Fig. 2.2 depicts working path (a-b-c-d-e-f) with path protection through (a-k-l-m-f). Signaling information is required to be communicated from the failure location to the end nodes

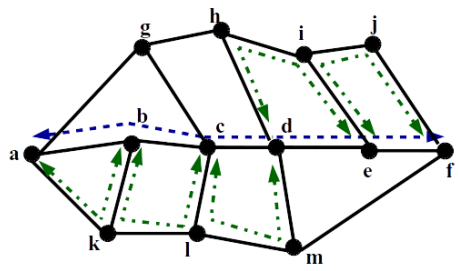


Figure 2.1: Network with link protection

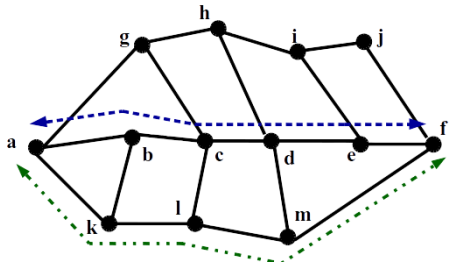


Figure 2.2: Network with path protection

of the path for switching the traffic over to protection path. Path protection may be categorized as a fault independent protection since protection path is same for any fault anywhere on the working path. Path protection also provides protection to the node failures on the working path. In path segment protection, working paths are divided into multiple path segments. These path segments are then independently provided protection routes. Fig. 2.3 illustrates path segments (a-b-c) and (c-d-e-f) of working path (a-b-c-d-e-f) protected by (a-k-l-c) and (c-l-m-f) respectively. Depending on the number of path segments, segment protection can be more capacity efficient than the path protection, and even more efficient for the shared protection. For shared protection, working paths or the path segments which share the backup paths must be link disjoint. Since there are more link disjoint path segments than disjoint paths, shared path segment protection is expected to be more efficient. Excessive routing required in case of large number of small segments is the overhead paid to gain the protection efficiency.

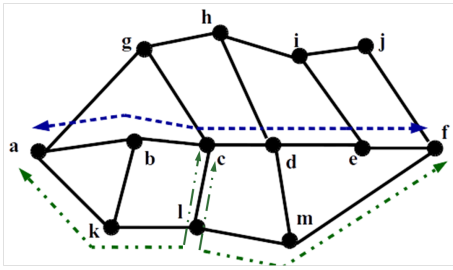


Figure 2.3: Network with segment protection

2.2 Ring Protection

Ring network is a widely used protection scheme in telecommunication networks. A ring is a simple 2-connected graph which provides protection route for any single failure within the ring network. A network with mesh topology can also be protected by deploying multiple rings within the network. Ring topologies can be differentiated by directionality of traffic on the ring or the protection mechanism used.

2.2.1 Och Dedicated Protection Ring

Fig. 2.4 shows an Och Dedicated Protection Ring (Och DPRing). Working and protection are provided on separate fibers in opposite direction. The source node generates two copies of signal and sends them on two different fibers in the opposite direction. In Fig. 2.4, traffic is sent simultaneously from node a to node b clockwise on the working fiber and anticlockwise on the protection fiber. Node b selects the best signal among the two received via working and protection fiber. Assume that node b selects signals received on working traffic under no failure condition. If the link between ab fails, b simply switches to the signal received on the protection fiber. The scheme is 1+1 dedicated protection as no signaling is required for switching of signals, only a selector is needed at the receiver end to select the best signal.

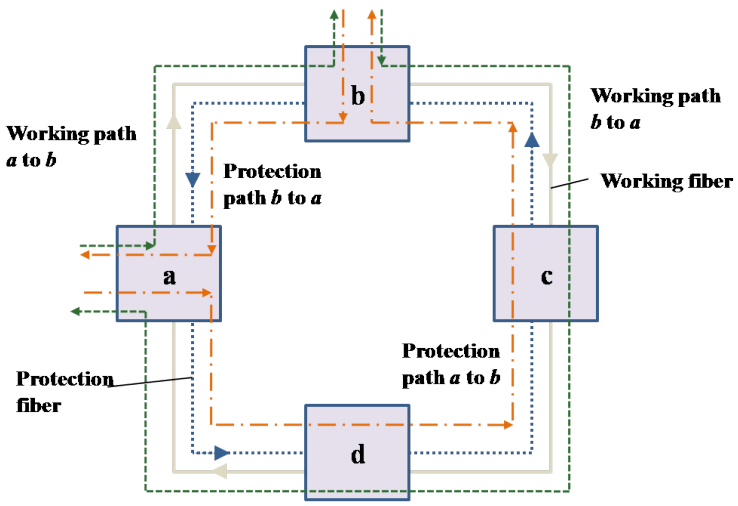


Figure 2.4: Protection of working path between node a and b using Och dedicated protection ring.

Each Och-DPRing can provide only one bidirectional connection and dedicated protection to it. In Fig. 2.4, the scheme utilizes one part of the fiber in one direction for working connection of a to b and the other part for the working connection in the reverse direction(b to a). The same holds true for other fibers which provide protection for a to b as well as for b to a using two non overlapping fiber ring segment in the pair. This scheme is same as a unidirectional path switched ring (UPSR) used in SDH.

2.2.2 Optical Multiplex Section- Shared Protection Ring (OMS-SPRing)

Fig. 2.5 depicts architecture and working of a Four fiber OMS shared protection ring (OMS-SPRing). Two fibers are used as working, and two fibers are used as protection. Working traffic can be transmitted in both the directions as opposed to Och-DPRing. As an example, working traffic flows in an anticlockwise direction from node b to node d, and in a clockwise direction from node d to node b.

In case of failure, the traffic at the end nodes of the failed link is switched on to the

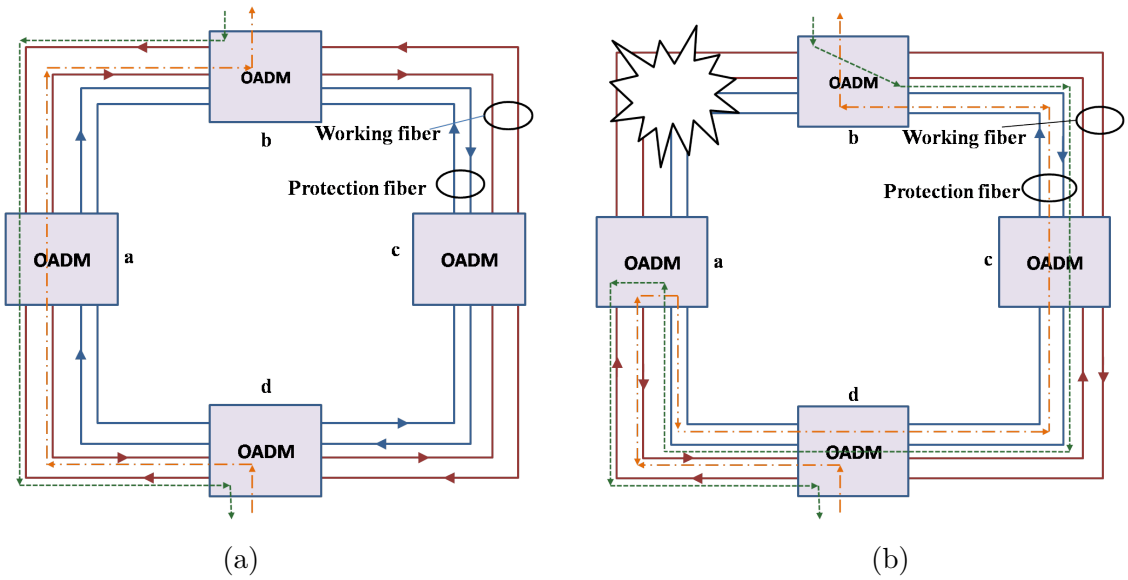


Figure 2.5: Working of OMS-SPRing. (a) Normal condition, and (b)Link failure.

protection fiber by loop back mechanism. Fig. 2.5 (b) shows a failure condition between node a and b. Switching takes place at node a and node b, protection route traversed by the traffic is as shown in Fig. 2.5 (b).

OMS-SPRings are capacity efficient since they provide shared protection among spatially distributed traffic on the ring. Two fiber OMS-SPRing can be realized by allocating half wavelengths for working capacity and half for the protection capacity on each fiber. For implementing two fiber OMS-SPRing, wavelength of working capacity on one fiber must correspond to protection wavelength on the other fiber. These mechanisms are same as the bidirectional line switched ring (BLSR) for four fiber and two fibers in SDH networks.

2.2.3 Ring Covers

This technique is used to protect mesh network. In this technique, a set of rings are found, which covers all the links in the network. In other words, each link of a network

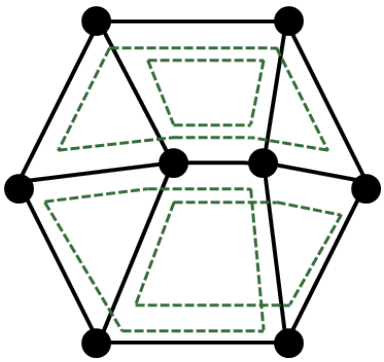


Figure 2.6: A possible ring cover implementation of a network.

is covered by at least one cycle. To cover all the links of the network, some links may need to have more than one ring. This implies that ring cover technique involves more than 100% redundant capacity. An example of a network with ring covers is shown in Fig. 2.6.

2.2.3.1 Cycle Double Covers

Cycle double covers (CDC) were first proposed by Ellinas *et al* [17] to protect mesh optical networks. To implement CDC, a mesh network is represented as a directed graph. Each working fiber requires exactly one protection fiber implying exactly 100% redundancy. Each link of the network is equipped with four unidirectional fibers. For each link, two fibers are used to carry traffic in both the directions. The remaining two are used for protection in directions opposite to that of working fiber. Protection fibers are used to form sets of directed cycles such that: each protection fiber occurs only once in any directed cycle. A pair of protection cycles is not used for the same cycle unless the link is a bridge (Bridge is an edge (or link) of a network graph, removal of which disconnects the network graph). Fig. 2.7 depicts a network with CDC protection. For any connected planar graph with v number of vertices's and e number of edges, *Euler's number* $f = 2 + e - v$. There are $(f - 1)$ number of inner faces and one outer face for

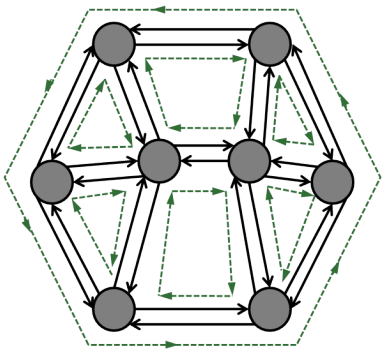


Figure 2.7: A possible cycle double cover protection implementation of a network.

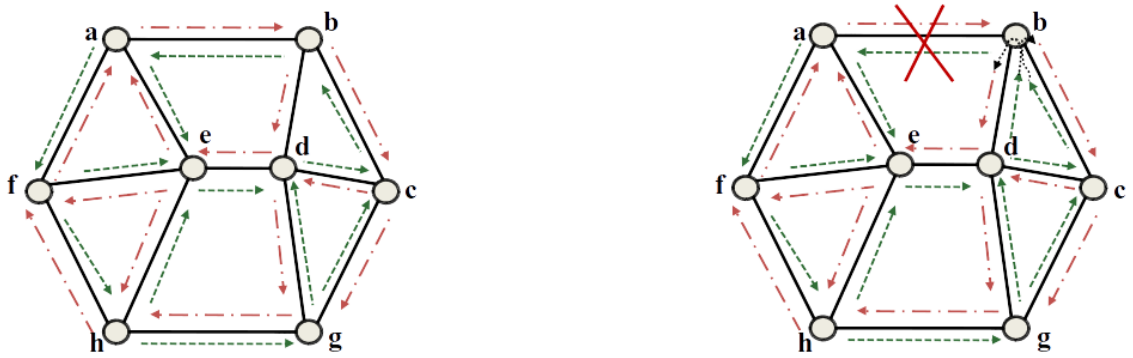
the planar graph. The obtained faces can be used to form the cycle's double covers for the network graph.

For non-planar graphs, heuristic algorithm have been applied to find the cycle double covers [18].

2.2.4 Generalized Loop-back

Generalized loop-back is a scheme for mesh network protection [19] [20]. In generalized loop-back, network graph is divided into primary and secondary subgraph, which are conjugate to each other. Primary subgraph is used to carry traffic while secondary provides backup protection. For simplicity assume that each link has two fibers in opposite direction. Subgraphs are formed by selecting one fiber for primary subgraph and second fiber for secondary subgraph from each link. In case of failure, wavelength on primary subgraph is looped back on the same wavelength on secondary subgraph. The signal floods through the network, reaches other end of the failed link and automatically switches back to the primary subgraph.

An example of generalized loop-back is demonstrated in Fig. 2.8. In Fig. 2.8, primary subgraph is shown by dash and secondary subgraph is shown by dash-dots. Consider



(a) (b)

Figure 2.8: Network with generalized loop-back primary (dash) and secondary(dash and dot) graph (a) Normal condition, and (b) protection.

failure of link ab. The working path traversing node b to a via link ab on primary subgraph gets loop-back at node b on the secondary subgraph. The flooded backup traffic of node b finds its path to node a. The backup traffic takes various possible paths to reach the destination node a. The path on which traffic arrives first on the destination node a is selected as backup path and all the other paths arriving later are discarded. The nodes that sent the subsequent traffic are notified by sending a negative acknowledgment to stop forwarding the traffic further. Thus, only one back up path is selected.

2.3 Pre-configured Cycle

Pre-configured Cycle (p-cycle) is a protection scheme in which cycles are formed in a mesh optical network using redundant capacity. P-cycles were first introduced by Grover [21] and gained significant interest from researchers due to the combined advantage of fast recovery and efficient utilization of redundant capacity. A p-cycle can

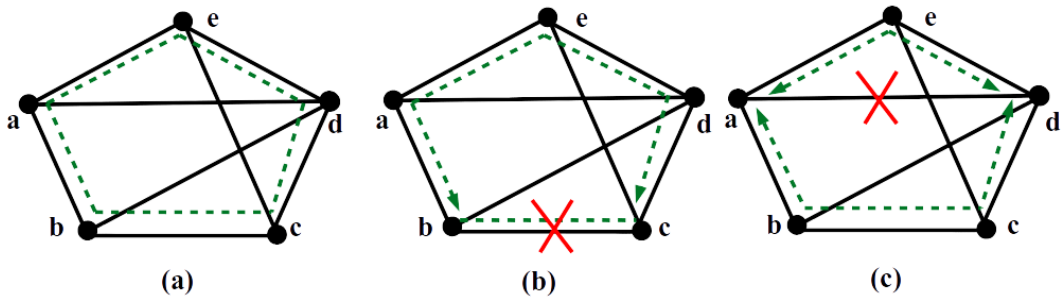
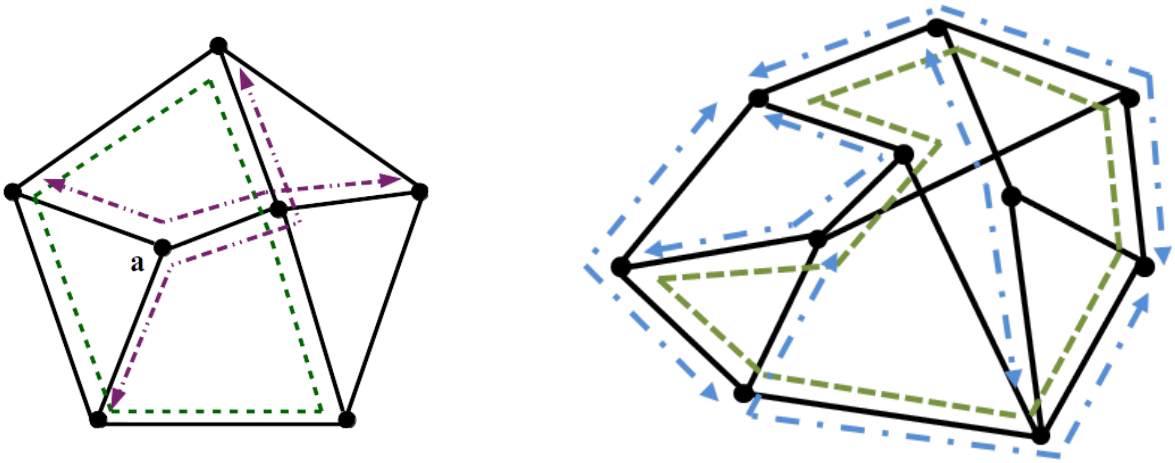


Figure 2.9: Illustration of protection using p-cycles.

protect working capacity of the on-cycle as well as the straddling links. A straddling link is a chord of a cycle with its end nodes being part of the cycle. When a straddling link fails, a p-cycle has two paths to reroute the traffic and hence, the capacity requirement in the p-cycle is reduced to half of the protected working capacity in the straddling link. A single copy of a p-cycle can provide unit capacity protection to an on-cycle link and two unit capacity protection to straddling links on it. Fig. 2.9 illustrates protection of a network from single link failure based on p-cycles. Fig.2.9(a) shows optical network with no failure and an idle p-cycle depicted by dotted line. In case of link failure, restoration is done by rerouting on the p-cycle, by switching the traffic at the two end nodes of the failed links. Since straddling link has two restoration routes (refer to Fig. 2.9 (c)), unit capacity of p-cycle can restore two working capacity of a straddling link. Restoration of on-cycle and straddling link using p-cycle is shown in Fig. 2.9(b) and (c) respectively.

Significant literature is available on various aspects of p-cycles. P-cycles can be used to protect nodes, links, paths or path segments in the optical network. Originating or terminating traffic of a failed node cannot be restored by rerouting or network level reconfiguration. Therefore only transiting flows are restored in case of node failure. Node encircling p-cycle (NEPC) were proposed to provide protection to transiting flows to each node of a network [22]. NEPC is a p-cycle which traverses all nodes adjacent to



(a) Node encircling p-cycle. (b) FIPP p-cycle

Figure 2.10: Illustration of protection through (a) Node encircling p-cycle, and (b) FIPP p-cycle.

the failed node and excludes the failed node. Transiting flows between adjacent nodes through the failed node thus gets rerouted on NEPC. Fig. 2.10 (a) depicts a NEPC (dotted line) which protects two transiting flows (dash-dots) through node a.

The concept of link protecting p-cycles is extended to path protection using failure independent path protecting(FIPP) p-cycles. FIPP p-cycle can protect all the disjoint paths which have their end nodes on the p-cycle. Fig. 2.10(b) shows FIPP p-cycle (green dotted) protecting disjoint paths indicated by dash-dot lines.

More generalized protection would be the protection of demand flows over path-segments, which can be a portion of the whole end-to-end path, using path-segment or flow-protecting p-cycles. The capacity efficiency offered is higher by path-segment or flow-protecting p-cycles than link protection p-cycles. Implementation of flow p-cycles based protection over an entire network would be complex and slow as signaling is required on the flow path to tell the end nodes of the flow path on the p-cycle to switch over to the protection path.

Finding any type of p-cycles with least resources for a network is an optimization prob-

lem. Design approach with p-cycle can be broadly categorized into centralized and distributed methods. In a centralized method, p-cycles are selected from the set of all the cycles satisfying the chosen criteria in the network graph. Integer linear programming (ILP) method is a centralized optimization method. ILP optimization includes spare capacity optimization, joint capacity optimization or protected working capacity envelope optimization. In spare capacity optimization, a set of p-cycles are selected from the pre-computed set of cycles using optimization model to protect working capacities of the network. Joint capacity optimization involves finding optimum capacities required to form working paths and p-cycles together. Joint capacity optimization is more complex than the spare capacity optimization and takes a longer time to solve. In protection working capacity envelope optimization(PWCE), p-cycles are found with an objective to cover maximum working channels. Later working paths or demands are routed within the protection envelope of p-cycles. ILP based approaches are studied extensively for static as well as dynamic traffic. The complexity in ILP method arises due to large number of variables involved in the formulation, and solution of ILP which comes under NP-hard problems. ILP approach gives quick results for small networks and is helpful in studying survivability of larger networks. ILP solvers can compute optimal or near optimal solution for networks as large as having 100 nodes. Heuristic algorithms are also used to design p-cycle based networks. Heuristic algorithm requires less time as compared to ILP method. ILP methods are more capacity efficient than heuristic algorithms. Extensive summary of research on p-cycles can be found in [23] [24].

2.4 Multiple Failures in Optical Network

Survivability schemes described in the earlier sections of this chapter provide single failure protection, which means that they provide 100% single failure protection in a given network. Restoration of traffic on the preassigned backup path is a rapid process, but repair of the failed link may take hours. In the meantime, another failure might occur in the network. Sometimes, multiple simultaneous failures may occur due to common events such as an earthquake, hurricane, etc. Multiple failures arising due to a common event are called as correlated failures. Multiple simultaneous failures may also occur within the network due to uncorrelated events. Failure probability of two links with overlapping protection can be frequent enough to be taken into consideration for protection [25] [26].

Multiple failures created by natural disasters as well as human-created disaster such as weapon of mass destruction can be considered as correlated failures. Natural disasters can greatly affect telecommunication as seen by various natural calamities in the past [27]. Studies on disaster survivability of optical network include modeling of multi-failure scenarios based on statistical data and geographical location of disaster-prone areas. Studies include designing intelligent networks which can sustain high priority traffic during a disaster and able to recover fast. Disaster failure models can be classified as *deterministic* or *probabilistic*. Deterministic approach models the failures with equal probability within a specific disaster zone [28]. Probabilistic approach considers intensity and proximity-based probability of failures to model the occurrence of failure [29] [30] [31].

Various approaches have been suggested to administer multi-failures caused by disasters. One of the approaches is to model the disaster regions as shared risk link groups (SRLG) and then provide a disjoint pair of working and backup paths for links in the

network [32] [33]. Multipath routing has also been studied to reduce multiple failures [34] [35]. In multipath routing, the data is divided and sent over multiple disjoint paths to speed up the overall transmission. Few reactive schemes have also been proposed to combat multiple failures, which involves re-provisioning and re-optimization of network capacity for existing connections [36] [37] [38]. Provisioning of protection for multiple failures arising due to disasters may be costly, hence deciding the level and extent of protection to multiple failures is also an important aspect.

2.4.1 Two-Link/Double-link Failure Protection

Protection against two-link failure requires higher resources than single link protection. The two-link protection optimization problem has higher complexity due to larger number of variables as compared to a single link failure protection optimization. The efforts in the research are directed to bring down the capacity requirement and complexity of the optimization problem. There are various two-link protection approaches. These can be categorized as, dedicated and shared protection, link and path protection, exhaustive and selective protection and static and dynamic protection.

2.4.1.1 Dedicated and Shared Protection

Dedicated protection for single link failures can be extended to two-link failures. Three disjoint paths between the source and destination nodes can be used: one path for working traffic and the other two can be used as back up paths for protection. Dedicated protection for two-link protection requires excessive resources, and therefore should only be used for few stringent demands. A combination of dedicated and shared

protection can also be used to protect the network from two-link failure. One option is to use 1+1 dedicated protection to the most probable first link failure and provide shared protection to the second link failure. The most capacity efficient way is to provide shared protection to both failed links.

2.4.1.2 Availability Analysis and Two-link Protection

A network designed for single link protection has some inherent double link protection. For example, two simultaneous failures in a network with non overlapping protection are simultaneously restorable. Availability is referred to as the time for which demands/services are functional in a network. In literature, various availability metrics are defined to quantify and optimize double link failure protection in a full single link protected network [39] [40] [41] [42]. Indirect measures of availability analysis includes number of non-restored working capacity (NWC) and restorability (R). The term, service path unavailability (SPU) is used for direct calculation of network unavailability. A subscript of 1 and 2 is used to differentiate between single and double fault scenarios respectively. In [43] [44], Schupke studied various dual link failure survivability cases with p-cycles. The p-cycles of the network were configured with different objectives, and dual failure restorability (R) was compared for each case. For example, R_1 refers to single link restorability while R_2 is referred to as double link restorability. It was observed that maximizing the number of p-cycles yields better restorability at the expense of higher required capacity and minimizing the maximum working capacity coverage of p-cycles is capacity efficient and gives better dual failure restorability [43] [44]. Li *et al* developed an ILP model in [40] to protect networks from single link failures with specified double link restorability. In [41], the author proposed a new dual-failure unavailability metric

as the *specific number of lost path based dual-failure service path unavailability* (SDU), which considers the failed service path shared by the two simultaneously failed links. The author proposed an ILP model to optimize non-restored working capacity for two link failure (NWC_2) for given *minimum cost to guarantee full single link failure restorability* (B) and NWC_{tar} (the target value of the objective function). The ILP model is solved for some specific number of times. Values of NWC_2, R_2, SPU_2 and SDU obtained from each iteration are used as input for the next iteration. The work suggests that NWC_2, R_2 and SPU_2 does not provide direct dual-failure service availability analysis, while proposed SDU is a more accurate expression for dual-failure unavailability. Simulation results suggest that minimizing NWC_2 maximizes R_2 and minimizes SPU_2 [41]. Extending dual failure restorability study further in [45], a p-cycle based design is proposed to give a quality of service based double link failure protection in an optical network.

2.4.1.3 Loop-back Recovery Schemes

Loop-back recovery method has been explored by researchers for double-link protection in optical networks. Choi *et al* [46] proposed three loop-back recovery methods for double link failure survivability. The first two methods require identification of the failed link for choosing and implementing the backup paths. The third loop-back recovery method preselects a single backup path for each link to provide protection from any two link failures. In [46], an algorithm was described to compute the backup path required to implement loop-back recovery method. The algorithm achieved almost full double link failure recovery with a modest increase in backup capacity as compared to WDM loop-back recovery [47] and shortest backup path algorithms. In [48], loop-back

recovery schemes for double link failure protection have been implemented using integer linear program formulation for dedicated and shared protection. Shared loop-back protection provides 10-15% capacity savings over dedicated protection.
Some dynamic recovery schemes have also been provided in the literature [49] [50] [51]. In [49] an adaptive backup routing over reserved resources (ABRRR) has been proposed. In this scheme, a certain percentage of the total wavelengths on each link are reserved for establishing backup paths. The backup paths are searched dynamically after the occurrence of failure and wavelengths are assigned to establish a recovery path for the connection. Zhang *et al* [50] proposed a new dynamic rerouting (NDR) algorithm to compute backup path dynamically for the precomputed working paths. A heuristic algorithm proposed by Guo [51], *routing with optimal solution* (ROS) searches for better working and backup paths dynamically as an optimal solution until limiting count is reached, or the new solution is worse than the previous solution. In [52], a hybrid scheme is proposed for two-link failure protection. In this scheme, one backup path is reserved for each working path to ensure full single link protection. Second link failure is restored by computing backup path around the failed link.

2.4.1.4 Dynamic Recovery Schemes

An algorithm has been introduced in [53] to find k-disjoint p-cycles to protect a network from k-link failures. Feng *et-al* [54] proposed two-link failure protection schemes based on p-cycles. They formulated an ILP to obtain p-cycles for the static traffic. Two protection schemes, shortest path pair protection (SPPP) and short full path protection (SFPP) were also proposed to protect the dynamic traffic from two-link failure. All the schemes described in [54] require two p-cycles with link disjoint backup paths for each

link in order to protect from two-link failure. In [55], an algorithm is proposed to provide protection to working routes from specified one or two failures. An algorithm has been proposed in [55] which uses path protection p-cycles for dual failure restoration. The algorithm ensures the availability of at least one back up route for demands requiring double fault protection.

2.4.1.5 Novel Structures for Two-link Protection

Some novel two-link protection approaches have also been proposed in the literature. The concept of Pre-configured Polyhedron (PCP) [56] has been introduced for protecting a network from multi-link failures. The drawback of this scheme is that it requires searching of backup paths within the PCP before switching. Pre-configured ball (p-Ball) [57], consisting of a ring set for dual link failure uses minimum backup links for dual link failure restoration. P-Ball uses a routing algorithm to find back up paths from the ring set after failure, which increases the restoration time. In [58], a Tie-set Based Fault Tolerance (TBFT) method to recover double-link failures has been introduced. In this method, an autonomously distributed control method finds a set of tie-sets in the network such that their union covers all the edges of the network. Zhang *et-al* [59] proposed preconfigured k-edge-connected structures (p-$k$ecs) for protection from multiple link failures in optical network. P-$k$ecs are the subgraph of original physical topology which contains k link-disjoint paths between any two distinct nodes.

Chapter 3

Improved Double Cycle Method

In this chapter, we have described double cycle method (DB) along-with an improvement named as improved double cycle method (IDB). The DB and IDB are deterministic methods to protect optical networks from two simultaneous link failures. In DB as well as IDB, working capacity of each link is protected using pairs of p-cycles providing link disjoint back up paths. In IDB method, priorities are set among the p-cycles forming a pair to protect the link. The strategy of setting priorities among p-cycles of a pair reduces the spare capacity required by the optical network. The computational resources required to devise the solution is also less as compared to the DB method.

3.1 Double Cycle Method

The method described in [54] use two p-cycles with link-disjoint backup paths to protect a link from two simultaneous link failure. We have considered a bidirectional graph $G(N, L)$ and formulated an alternative ILP using the concept of two p-cycles for protecting each link from two simultaneous failure. Alternative p-cycle is simple and elegant. Here, N is the number of nodes and, L is the number of links in the given

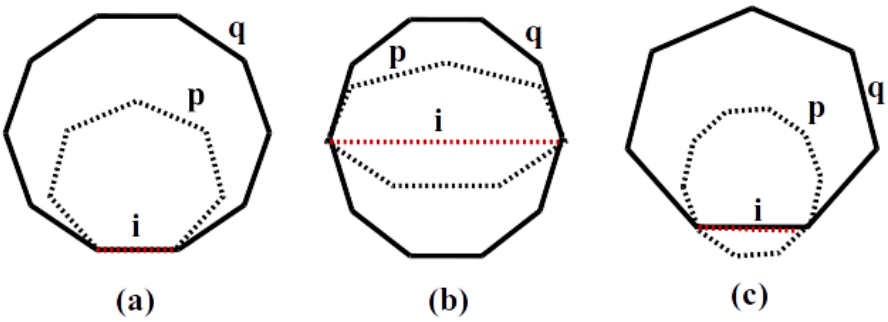


Figure 3.1: Various possibilities for protection-pair of p-cycles (p and q) which can protect the link i from two simultaneous link failure.

optical network. Set of cycles, and set of pairs of p-cycles for each link are precomputed and given as an input to the optimization model. There are three different possibilities in which two p-cycles can form a pair to protect a link from two simultaneous link failures, as shown in Fig. 3.1 (a),(b) and (c).

Protection-Pair: A protection-pair for link i is defined as a pair of p-cycles which are link disjoint or have only one link i as the common on-cycle link and they both can be used to protect the link.

For each link, Protection-Pairs are chosen independently. One p-cycle can be shared among multiple protection-pairs for protecting more than one link. In some cases, the same Protection-Pair can protect more than one link. Possible scenarios when a Protection-Pair can protect more than one link are shown in Fig. 3.2. Table 3.1 illustrates possible two-link failures and the number of copies of p-cycle p and q required to protect links i and j from the failure. Possible scenarios when two p-cycles can protect only one link are shown in Fig.3.1.

Fig. 3.2 (a) shows the case in which two links i and j are 'on-cycle' on p-cycle q and 'straddling' on p-cycle p. If link i fails, protection is provided by one of the p-cycles from the pair. If the second failure occurs on the p-cycle which is used to restore the

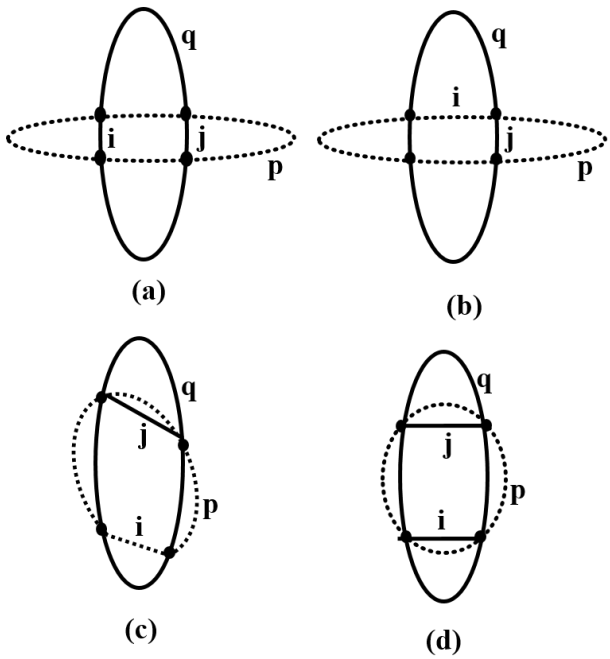


Figure 3.2: Links sharing same pair of protecting p-cycles

first failure, then the traffic is diverted on to the unused p-cycle of the pair. Link j is also protected by the pair of p-cycles p and q in the same way. In case of simultaneous failure of both the links i and j, the p-cycle q fails to protect the links, and traffic for both the links is restored by the p-cycle p. The required number of copies of p-cycles p and q should be sufficient to incorporate all the two failure scenarios mentioned above. All the possible two link failure scenarios for case of Fig. 3.2 (a) is described in Table 3.1. The overall copies of the p-cycles required to protect worst case failures is also given in Table 3.1. In Table 3.1 C_i and C_j represent the working capacity of link i and j respectively protected by protection-pair of p-cycles p and q. To ensure protection for the three cases shown in Fig. 3.2 (b), 3.2(c) and 3.2(d) number of copies of p-cycles p and q required will be the what is needed to protect the maximum of the capacities on links i and j (see Table 3.1). In case of simultaneous failure of links i and j, the p-cycles p and q protect links i and j respectively for these cases.

Table 3.1: Protection-pair sharing cases in DB method

Case (refer to Fig. 3.2)	Failed link	$n_p \geq$	$n_q \geq$
(a) i and j straddling on p, i and j on-cycle on q	i and any link on p	–	C_i
	i and any link on q	$\frac{C_i}{2}$	–
	j and any link on p	–	C_j
	j and any link on q	$\frac{C_j}{2}$	–
	i and j	$\frac{C_i}{2} + \frac{C_j}{2}$	–
	Overall	$\frac{C_i}{2} + \frac{C_j}{2}$	$max(C_i, C_j)$
(b) i on-cycle on p and straddling on q, j on-cycle on q and straddling on p	i and any link on q	C_i	–
	i and any link on p	–	$\frac{C_i}{2}$
	j and any link on p	–	C_j
	j and any link on q	$\frac{C_j}{2}$	–
	i and j	C_i	C_j
	Overall	$max(C_i, \frac{C_j}{2})$	$max(\frac{C_i}{2}, C_j)$
(c) i on cycle on p straddling on q, j straddling on p and q	i and any link on q	C_i	–
	i and any link on p	–	$\frac{C_i}{2}$
	j and any link on q	$\frac{C_j}{2}$	–
	j and any link on p	–	$\frac{C_j}{2}$
	i and j	C_i	$\frac{C_j}{2}$
	Overall	$max(C_i, \frac{C_j}{2})$	$max(\frac{C_i}{2}, \frac{C_j}{2})$
(d) i and j straddling on p and q	i and any link on p	–	$\frac{C_i}{2}$
	i and any link on q	$\frac{C_i}{2}$	–
	j and any link on q	$\frac{C_j}{2}$	–
	j and any link on p	–	$\frac{C_j}{2}$
	i and j	$\frac{C_i}{2}$	$\frac{C_j}{2}$
	Overall	$max(\frac{C_i}{2}, \frac{C_j}{2})$	$max(\frac{C_i}{2}, \frac{C_j}{2})$

3.1.1 Integer Linear Program for DB Method

This integer linear program (ILP) finds the minimum spare capacity required to form p-cycles, ensuring the protection of each link against two simultaneous link failures using double cycle method.

Notations

S=set of spans.

P=set of cycles.

Q_i=set of protection-pairs of link i, indexed as $(p,q)_i$.

For a link i having $(p,q)_i$ in the set Q_i, we define the indicator variable $x_{i,p,q}$ as follows,

$$x_{i,p,q} = \begin{cases} 1 & \text{if link } i \text{ is on-cycle link on p-cycle } p, \\ 2 & \text{if link } i \text{ is straddling link on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

We also define the indicator variable $\delta_{i,j}$,

$$\delta_{i,p} = \begin{cases} 1 & \text{if link } i \text{ is on-cycle on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

Variables

s_i =spare capacity on link i.

w_i =working capacity on link i.

c_i=cost of unit capacity of link i.

n_p = number of copies of p-cycle p.

$n_{i,p,q}$=number of copies of p-cycle p required to protect link i in pair with p-cycle q to protect link i from two simultaneous failure.

$n_{i,p}$=number of copies of p-cycle p required to protect working capacity of link i.

Minimize:

$$\sum_{i \in S} c_i s_i. \tag{3.1.1}$$

Subject to :

$$\sum_{(p,q)_i \in Q_i} [x_{i,p,q} n_{i,p,q} + x_{i,q,p} n_{i,q,p}] \geq 2w_i; \qquad \forall i \in S. \tag{3.1.2}$$

$$n_{i,p,q} = n_{i,q,p}; \quad \forall i \in S; \forall (p,q) \in Q_i | x_{i,p,q} = x_{i,q,p}. \tag{3.1.3}$$

$$n_{i,p,q} = 2n_{i,q,p}; \quad \forall i \in S; \forall (p,q) \in Q_i | x_{i,p,q} = 1, x_{i,q,p} = 2. \tag{3.1.4}$$

$$n_{i,p} = \sum_{q \in P, q \neq p} n_{i,p,q}; \quad \forall p \in P, \forall (p,q) \in Q_i. \tag{3.1.5}$$

$$n_p \geq n_{i,p} + n_{j,p,q}; \quad \forall i \in S; \forall (p,q) \in Q_j \cap Q_i; \tag{3.1.6}$$

$$i, j \in q; i \neq j.$$

$$s_i \geq \sum_{p \in P} n_p \delta_{i,p}; \quad \forall i \in S. \tag{3.1.7}$$

$$n_p \geq 0, n_{i,p} \geq 0, n_{i,p,q} \geq 0; \quad \forall i \in S; \forall p \in P; \forall (p,q) \in Q_i. \tag{3.1.8}$$

The objective function (3.1.1) minimizes the total required spare capacity of the network. Constraint (3.1.2), (3.1.3) and (3.1.4) ensure full protection of working capacity of each link against two simultaneous link failure. Constraint (3.1.3) ascertains that number of copies of p-cycles in a protection-pair are equal if the protected link is either on-cycle or straddling to both the p-cycles (refer to Fig. 3.1 (a), (b)). To protect a link which is on-cycle on one of the p-cycle of the protection-pair and straddling on the other p-cycle as shown in Fig. 3.1 (c), the number of copies of p-cycle having the link as on-cycle must be twice the number of copies of the p-cycle having the link as straddling. Constraint 3.1.4 ensures it.Constraint (3.1.5) calculates the number of copies of a p-cycle p required to protect a link i as the sum of number of copies of the p-cycle p in

pair with other p-cycles q required to protect the link i. Constraint (3.1.6) ensures that the number of copies of p-cycle is sufficient to protect the link with highest working capacity. Constraint (3.1.6) also takes care of the case when two links share same pair of p-cycles as described in this section earlier and illustrated in Fig(3.2). Constraint (3.1.7) ensures that spare capacity on each link is sufficient to form the p-cycles.

3.2 Improved Double Cycle Protection Method

In IDB each link in a network has protection-pair p-cycles to protect the link from two simultaneous link failures. The protection-pair consists of a primary, and a secondary p-cycle. When the first failure occurs, traffic is diverted on the primary p-cycle. The protection path is switched to secondary p-cycle if any link on primary p-cycle fails. Fig.3.1 shows valid pairs of p-cycles which can protect a link from two simultaneous link failures. In the Fig.3.1 (a), link i is on-cycle to both p-cycles (p and q) of the pair. In this case, the number of copies of both the p-cycles required to protect link i should be equal to the working capacity of the link. In this case, any of the p-cycle from the pair can be selected as primary p-cycle and the other p-cycle as secondary p-cycle. Selection does not affect the spare capacity in this case.

In Fig.3.1 (b), link i is straddling on p-cycles p and q. In this case, any of the p-cycles from the protection-pair can be selected as primary p-cycle and the other as secondary p-cycle. The number of copies required by primary p-cycle will be half the working capacity of link i. The number of copies of secondary p-cycle required will be quarter of the working capacity of link i, as the failure of a link on primary p-cycle affects only half of the restored traffic. To keep the ILP simple and reduce the number of variables, we have taken number of copies of both the p-cycles in the protection-pair equal to half

of the working capacity of the link i.

In the third case, Fig. 3.1 (c), link i is on-cycle on q, and straddling on p. In this case p-cycle p is used as primary p-cycle, and q is chosen as secondary p-cycle. If link i fails, traffic is diverted on p. If the second link failure occurs on p-cycle p, half of the traffic gets affected since only one of the backup path of p is failed. The affected traffic is diverted on secondary p-cycle q. The number of copies of both the p-cycles p and q required is half the working capacity of the link i. By choosing p as primary p-cycle, and q as secondary p-cycle, the number of copies of p-cycle q required is reduced to half, which in turn reduces the required spare capacity.

The strategy of using primary p-cycle from the pair of p-cycle, on which protected link is straddling reduces the overall spare capacity required. Also, the required number of copies of the p-cycles in the pair is same for both the p-cycles in all the three cases (Fig.3.1) as described in the preceding paragraphs of this subsection. Therefore, variables used to represent the number of copies of primary and secondary p-cycles to protect the link can be represented by a single variable. As a consequence number of variables and constraints required in the ILP formation are reduced as compared to DB method.

Different protection-pairs can share protection capacity of the p-cycle which is common among them. If one of the p-cycle in the protection-pair of links is common, then the number of copies of the p-cycle is kept equal to the maximum of the working capacity of the links. The case where both the p-cycle in the protection-pair of the links are common, the number of copies of the p-cycles required depends on the location of the links on the p-cycles. Four different cases in which the same protection-pair of p-cycles is common for two links are shown in Fig.3.2. Table 3.2 describes the various failure scenarios for each case and number of copies of p-cycles required to restore the fault. The number of copies of p-cycles should be sufficient to restore all the possible failures

for which the pair of p-cycles is accountable.

Let, c_i and c_j be the capacities of links i and j respectively, which are protected by the pair of p-cycles p and q. Consider case (a) in Fig.3.2 and Table 3.2. The number of copies of p-cycles p and q should be sufficient to restore failure requiring highest capacity. To protect capacities of links i and j, $2n_q \geq max(c_i, c_j)$ and $2n_p \geq (c_i + c_j)$. Where n_p and n_q are number of copies of p-cycles p and q respectively.

Fig.3.2(b), shows the case in which the two links i and j share protection-pair of p-cycles p and q. Link i is on-cycle on p-cycle p and straddling on q. While link j is on-cycle on q and straddling on p. The maximum capacity to be restored by p-cycle p as well as q is $\frac{c_i}{2} + \frac{c_j}{2}$. Therefore, $2n_p \geq c_i + c_j$ and $2n_q \geq c_i + c_j$

In Fig.3.2 (c), link j is straddling on both the p-cycles p and q of the pair. Any one of the p-cycle p or q can be chosen as primary p-cycle for link j. To protect capacities c_i and c_j, relations $2n_p \geq max(c_i, c_j)$ and $2n_q \geq (c_i + c_j)$ should hold.

In Fig.3.2 (d), link i and j are straddling on both p and q. We can infer from Table 3.2 that, to protect capacities of link i and j, $2n_p \geq max(c_i, c_j)$ and $2n_q \geq max(c_i, c_j)$ relationships should be satisfied.

Various possibilities for which more than one link share a common protection-pair are shown in Fig.3.2. Table 3.2 illustrates various failure scenarios in each case, and the number of copies of p-cycles required to restore the fault. The number of copies of p-cycles should be sufficient to restore all the possible failures for which the protection-pair is accountable.

Table 3.2: Cases of two links sharing same protection-pair in IDB method

Case (Refer to Fig. 3.2)	primary p-cycle for i	Primary p-cycle for j	Failed link	Minimum achievable		To simplify ILP	
				$n_p \geq$	$n_q \geq$	$n_p \geq$	$n_q \geq$
(a) i and j straddling on p, i and j on-cycle on q	p	p	i and a link on p	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and a link on p	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	$\frac{C_i}{2}+\frac{C_j}{2}$	–	$\frac{C_i}{2}+\frac{C_j}{2}$	–
			Overall	$\frac{C_i}{2}+\frac{C_j}{2}$	$max(\frac{C_i}{2},\frac{C_j}{2})$	$\boldsymbol{\frac{C_i}{2}+\frac{C_j}{2}}$	$max(\frac{C_i}{2},\frac{C_j}{2})$
(b) i on-cycle on p and straddling on q, j on-cycle on q and straddling on p	q	p	i and a link on q	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and any link on p	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	$\frac{C_i}{2}+\frac{C_j}{2}$	$\frac{C_i}{2}+\frac{C_j}{2}$	$\frac{C_i}{2}+\frac{C_j}{2}$	$\frac{C_i}{2}+\frac{C_j}{2}$
			Overall	$\frac{C_i}{2}+\frac{C_j}{2}$	$\frac{C_i}{2}+\frac{C_j}{2}$	$\boldsymbol{\frac{C_i}{2}+\frac{C_j}{2}}$	$\boldsymbol{\frac{C_i}{2}+\frac{C_j}{2}}$
(c) i on cycle on p straddling on q, j straddling on p and q	q	q	i and a link on q	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and a link on q	$\frac{C_j}{4}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	0	$\frac{C_i}{2}+\frac{C_j}{2}$	0	$\frac{C_i}{2}+\frac{C_j}{2}$
			Overall	$max(\frac{C_i}{2},\frac{C_j}{4})$	$\frac{C_i}{2}+\frac{C_j}{2}$	$max(\frac{C_i}{2},\frac{C_j}{2})$	$\boldsymbol{\frac{C_i}{2}+\frac{C_j}{2}}$
	q	p	i and a link on q	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and a link on p	$\frac{C_j}{2}$	$\frac{C_j}{4}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	0	$\frac{C_i}{2}+\frac{C_j}{2}$	0	$\frac{C_i}{2}+\frac{C_j}{2}$
			Overall	$max(\frac{C_i}{2},\frac{C_j}{4})$	$\frac{C_i}{2}+\frac{C_j}{4}$	$max(\frac{C_i}{2},\frac{C_j}{2})$	$\boldsymbol{\frac{C_i}{2}+\frac{C_j}{2}}$
(d) i and j straddling on p and q	p	q	i and a link on p	$\frac{C_i}{2}$	$\frac{C_i}{4}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and a link on q	$\frac{C_j}{4}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	$\frac{C_i}{2}$	$\frac{C_j}{2}$	$\frac{C_i}{2}$	$\frac{C_j}{2}$
			Overall	$max(\frac{C_i}{2},\frac{C_j}{4})$	$max(\frac{C_i}{4},\frac{C_j}{2})$	$max(\frac{C_i}{2},\frac{C_j}{2})$	$max(\frac{C_i}{2},\frac{C_j}{2})$
	q	p	i and a link on q	$\frac{C_i}{4}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$	$\frac{C_i}{2}$
			j and a link on p	$\frac{C_j}{2}$	$\frac{C_j}{4}$	$\frac{C_j}{2}$	$\frac{C_j}{2}$
			i and j	$\frac{C_j}{2}$	$\frac{C_i}{2}$	$\frac{C_j}{2}$	$\frac{C_i}{2}$
			Overall	$max(\frac{C_i}{4},\frac{C_j}{2})$	$max(\frac{C_i}{2},\frac{C_j}{4})$	$max(\frac{C_i}{2},\frac{C_j}{2})$	$max(\frac{C_i}{2},\frac{C_j}{2})$

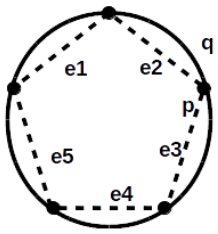


Figure 3.3: Protection-Pair of p-cycles shared by more than two links

There can be cases where more than two links can have the same pair of protecting p-cycles. Fig. 3.3 shows an example in which five links are protected by the same pair of p-cycles p and q. All the links $(e_1 - e_5)$ that can be protected by pair p and q are on-cycle and straddling on p-cycle p and q respectively. Since we are assuming only two-link failure at a time protection of all the five links is ensured by keeping the number of copies of p-cycle p equal to the highest working capacity of the five links. The number of copies of p-cycle q should be the sum of the capacity of the highest working capacity link and the second highest working capacity link.

3.2.1 Integer Linear Program for IDB method

Integer linear program stated below finds minimum spare capacity required to form p-cycles, ensuring protection of each link against two simultaneous link failures using IDB method.

Notations

S=set of spans.

P=set of cycles.

Q_i=set of protection-pairs for link i, indexed as $(p, q)_i$.

We define the indicator variable $x_{i,p,q}$ as follows,

$$x_{i,p,q} = \begin{cases} 1 & \text{if link } i \text{ is on-cycle link on p-cycle } p, \\ 2 & \text{if link } i \text{ is straddling link on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

We also define the indicator variable $\delta_{i,j}$ as

$$\delta_{i,p} = \begin{cases} 1 & \text{if link } i \text{ is on-cycle on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

Variables

s_i =spare capacity on span i.

w_i =working capacity on span i.

c_i=cost of unit capacity of span i.

n_p = number of copies of p-cycle p.

$n_{i,p,q}$=number of copies of p-cycle p = number of copies of p-cycle q, of the pair $(p, q) \in Q_i$ required to protect link i against two simultaneous failure .

$n_{i,p}$=number of copies of p-cycle p required to protect link i.

Minimize:

$$\sum_{i \in S} c_i s_i \tag{3.2.1}$$

Subject to :

$$\sum_{(p,q)_i \in Q_i} x_{i,p,q} n_{i,p,q} \geq w_i; \qquad \forall i \in S. \tag{3.2.2}$$

$$n_{i,p} = \sum_{q \in P, q \neq p} n_{i,p,q}; \quad \forall (p, q) \in Q_i. \tag{3.2.3}$$

$$\begin{aligned} & n_p \geq n_{i,p} + n_{j,p,q}; \quad \forall i, j \in S; \\ & \forall (p, q) \in (Q_j \cap Q_i) \text{ and } [(i, j \in q) \text{ or } (i \in p; j \in q)]. \end{aligned} \tag{3.2.4}$$

The addition of variable $n_{j,p,q}$ in the eqn. 3.2.4 above corresponds to the situation highlighted in Table 3.2.

$$s_i \geq \sum_{p \in P} n_p \delta_{i,p}; \quad \forall i \in S \tag{3.2.5}$$

$$n_p \geq 0, n_{i,p} \geq 0, n_{i,p,q} \geq 0; \quad \forall i \in S; \forall p \in P; \forall (p,q) \in Q_i. \tag{3.2.6}$$

The objective function (3.2.1) minimizes the total spare capacity needed in the network. Constraint (3.2.2) ensures full protection of working capacity on each link from two simultaneous link failures. Constraint (3.2.3) calculates the number of copies of p-cycle p required to protect link i, as the sum of number of copies of the p-cycle p in pair with the other p-cycles q required to protect the link i. Constraint (3.2.4) ensures that, the number of copies of p-cycle p is sufficient to protect the link with highest capacity, among all the links protected by the p-cycle. Constraint (3.2.4) also ensures protection of links which share p-cycle pair as explained in Table 3.2, and shown in Fig.3.2. Constraint (3.2.5) ensures that spare capacity on each link is sufficient to form p-cycles.

3.3 Complexity Analysis of ILPs

The complexity of integer linear program also depends considerably on the number of variables and constraints [60]. In this section, we calculate the number of variables and constraints involved in the formulation of ILP of two p-cycle methods in [54], DB, and IDB. DB and IDB method are based on the concept of using two p-cycles to protect unit working capacity on a link from two simultaneous link failures described in [54]. The technique described in [54] and DB is same but has different ILP formulation. Let

$G(N, L)$ be network graph with the N number of nodes and L number of links. P represents the set of cycles for the network and K be the working capacity on a link.

3.3.1 Complexity of ILP of DB Method

Number of variables required in the formulation of ILP are $2L + P + 2L.P^2 + L.P$.
Complexity of number of variables required is $O(L.P^2)$.
Number of constraints in the ILP is equal to the sum of number of constraint represented by each equation.
Number of constraints represented by eqn. 3.1.2 = L.
Number of constraints represented by eqn. 3.1.3 and 3.1.4 = $L.Q$ =$L.P^2$.
Number of constraints represented by eqn. 3.1.5 = P^2.
Number of constraints represented by eqn. 3.1.6 = $L.P^2$.
Number of constraints represented by eqn. 3.1.7 = L.
Number of constraints represented by eqn. 3.1.8 = $2L + L.P^2 + L.P + P$.
Total number of constraints required in the ILP formulation of ILP of DB method is $4L + P + P^2 + L.P + 4L.P^2$.
Complexity of number of constraint is $O(L.P^2)$.

3.3.2 Complexity of ILP of IDB Method

Number of constraints required in the formulation of ILP of IDB method is $2L + P + L.P^2 + L.P$
Complexity of number of variables required is $O(L.P^2)$.
Number of constraints in the ILP is equal to the sum of number of constraint represented by eqns. 3.2.2 to 3.2.6, and it is given as $4L + P + P^2 + L.P + 2L.P^2$.

Complexity of number of constraint is $O(L.P^2)$.

3.3.3 Complexity of Two-link Failure Method Described by Feng et-al in [54]

Number of variables required in the formulation of ILP eqn. (1) to (15) in [54] are $L + L.P + N.P + L.P.K + 4L^2.P.K$.

Complexity of number of variables required is $O(L^2.P.K)$.

Number of constraints in the ILP is equal to the sum of number of constraint represented by eqn. 3 to 15 in [54] is $L.K + L.P + N.P + L.P + N.L.P + K + L.P.K + 3L^2.P.K + L^2.P^2.K + L^2.P.K^2$.

Complexity of number of constraint is $O(L^2.P^2.K)$.

3.4 Results and Discussion

Simulations are performed on various network topologies shown in Fig. 3.4. Thirteen arbitrary test networks with different network parameters have been used for simulation. Scilab 5.5 was used for the ILP formulation. ILOG CPLEX 9 has been used to solve the ILP on AMD Opteron(tm) 1.8 GHz CPU. The networks Net2m, net3mod and net4 are taken from [61] and [62]. Since our methods are two-link failure protection methods, they apply to only 3-connected network graphs. A 3-connected graph is a graph which has three link disjoint paths for each pair of nodes. Non 3-connected graphs have been modified to 3-connected graphs by applying merge operation on them. A graph can be modified to a 3-connected graph by identifying the pair of nodes having less than three disjoint paths and performing following merge operations on them:

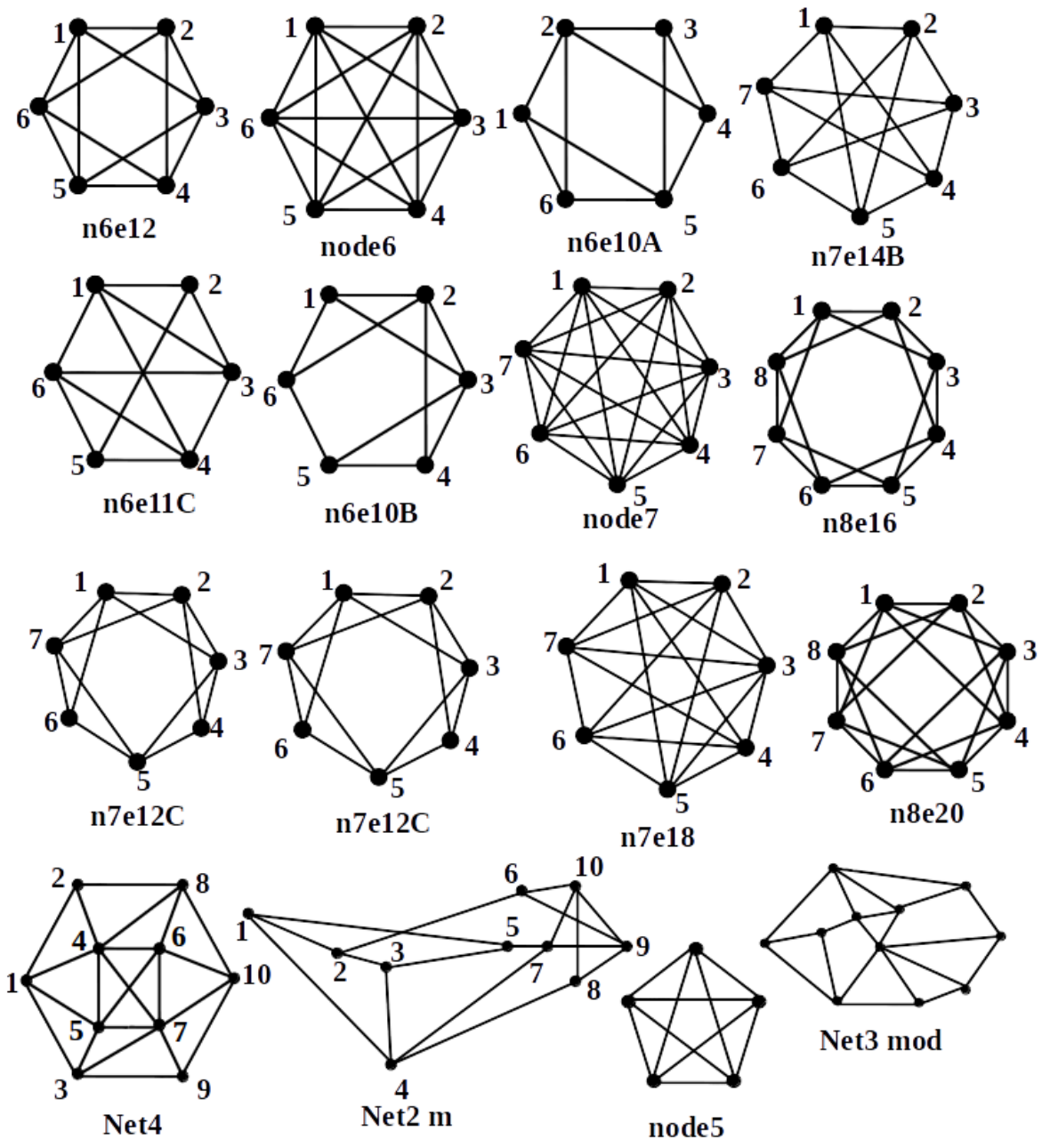


Figure 3.4: Networks used in simulation

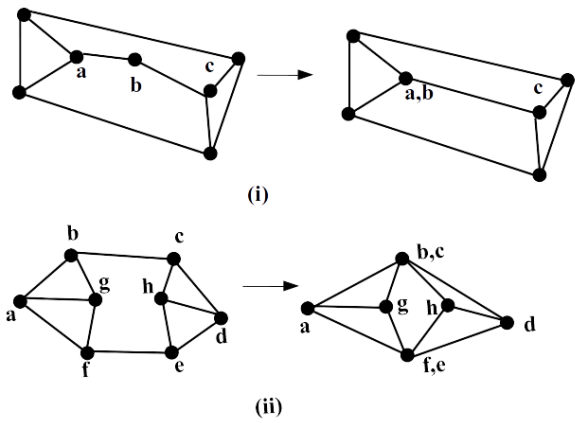


Figure 3.5: Illustration to modify a graph to a 3-connected graph

1. A node in a graph with degree two can be merged to a neighboring node. As an example in Fig. 3.5 (i) node b with degree two is merged with node a.

2. Node-pairs in a graph having less than three disjoint paths can be merged as illustrated in Fig. 3.5 (ii) to modify graph to a 3-connected graph.

The networks net2 (also known as NSFNET) and net3 have been modified to 3-connected graphs by applying merge operation explained above. For all the networks working paths have been obtained using shortest path algorithm assuming unit demand between each pair of nodes. Working capacity on each link is then computed by adding the working path traversed on the link. The computation of spare capacity efficiency (SE) and time needed to compute the result are given in Table 3.3. The ILP solver ILOG CPLEX uses the branch and cut algorithm to find out the most optimum solution. It compares the best node value to the objective function value of the incumbent solution. The gap is expressed as a percentage of the incumbent solution measures progress toward finding and proving optimality. A zero gap value indicates that optimality of incumbent solution has been proven. The value of gap is indicated in Table 3.3 only for the simulations stuck to the same nonzero value of gap and objective for more than 48hrs.

Definition Spare capacity efficiency (SE) is the ratio of spare capacity required for protection and the working capacity of network, and it is given by following eqn.

$$SE = \frac{\sum\limits_{\forall i \in S} s_i}{\sum\limits_{\forall i \in S} w_i} \tag{3.4.1}$$

where, s_i and w_i are spare capacity and working capacity respectively on link i.

Definition Average node degree: Degree of a node k is the number of links connected to it. Average node degree of a graph $G(N, L)$ is given by

$$< k >= \frac{\sum\limits_{\forall i \in N} k_i}{N} \tag{3.4.2}$$

where, k_i is the degree of node i, and N is the total number of nodes in the graph.

Low value of SE is desirable. IDB method requires less number of copies of protection-pair p-cycles than the DB method, for which link to be protected is on-cycle on one of the p-cycle and straddling on the other p-cycle of the protection pair. Consider a link i with w_i working capacity to be protected by protection-pair p-cycles $(p, q)_i$. Let, i be on-cycle and straddling on p and q respectively. DB method requires $n_{i,p,q} = w_i$ and $n_{i,q,p} = \frac{w_i}{2}$ while, IDB requires $n_{i,q,p} = n_{i,q,p} = \frac{w_i}{2}$ number of copies to protect the working capacity of link i. Simulation results in Table 3.3 show that SE is less in case of IDB method for most of the networks.

The ILP described in [54] has been designed for directed graphs. It involves calculating p-cycle for each unit of working capacity on a link. In addition to the number of links and set of p-cycles, the definition of variables and formulation of constraints requires identification of nodes as well as unit working capacity on the links. This makes the formulation of ILP more complex than DB and IDB method. We anticipate that the

ILP may not provide a solution for large networks. DB method offers the same solution as the ILP described in [54]. The computational complexity in the formulation of ILP in [54] is $O(L^2.P^2.K)$ while for DB and IDB is $O(L.P^2)$.

For IDB method, number of copies of p-cycles in a protection-pair is always equal, i.e, $n_{i,p,q} = n_{i,q,p}$. These two variables($n_{i,p,q}$ and $n_{i,q,p}$), thus can be represented by a single variable $n_{i,p,q}$ in ILP formulation. The total number of variables required by IDB method is, therefore, less than the number of variables required by DB method. Also, as the variables ($n_{i,p,q}$ and $n_{i,q,p}$), can be represented by a single variable $n_{i,p,q}$, constraints 3.1.3 and 3.1.4 are not required in the ILP of IDB method. The ILP of IDB is thus much simplified as compared to DB method. ILP formulation of IDB method needs less computational resources compared to DB method. The time required to solve ILP of IDB is also less as compared to DB method, (see Table 3.3). The results are more evident for larger networks and higher average node degree than the networks with low average node degree. The strategy of using primary and secondary p-cycle in a set of protection-pair reduces the spare capacity required. Therefore IDB performs better than DB and ILP model described in [54]. The complexity of ILP formulation of DB and IDB method is $O(L.P^2)$. The number of variables involved in ILP formulation is $O(L.P^2)$. ILP for these methods is unable to solve for networks having the number of cycles higher than 400.

Table 3.3: Simulation Results

Network	Avg. node degree $< k >$	Number of cycles	Working capacity	DB method SE	DB method ILP time (in sec)	IDB method SE	IDB method ILP time (in sec)
n6e10A	3.3	22	40	2.80	0	2.80	0
n6e10B	3.3	23	40	2.45	0	2.45	0
n7e12C	3.4	39	60	2.20	0.07	2.12	0
net2m	3.4	123	164	3.03	0.07	3.02	0.00
net3mod	3.4	256	198	2.57	22.54	2.55	8.68
n6e11C	3.6	39	38	2.63	0.01	2.55	0.06
n8e16	4	179	80	1.70 (gap=7.57%)	115906	1.24	9570.12
n7e14B	4	107	56	1.89	18487	1.36	144.55
n6e12	4	63	36	1.78	32.23	1.31	17.4
node5	4	37	20	1.5	4.12	1.00	1.17
net4	4.4	833	142	_	inf	_	inf
node6	5	197	30	1.00 (gap=48.87%)	52594	0.80 (gap=39.78%)	323468
n8e20	5	804	72	_	*inf	_	*inf
n7e18	5.1	459	48	_	*inf	_	*inf
node7	6	1172	42	_	*inf	_	*inf

*inf means solution could not be achieved by the machine used by us.

3.5 Conclusions

In this chapter, we have described DB and IDB methods for two-link failure protection in an optical network. ILP of DB and IDB method are less complex as compared to the ILP described by Feng *et al* [54]. The complexity of ILp formulation is $O(L^2.P^2.K)$ and that of DB and IDB is $O(L.P^2)$. Both DB and IDB method use two p-cycles to protect a link from two simultaneous link failure. For IDB method we have used priority among the p-cycle protection-pair which reduced the number of copies of p-cycles required and hence the spare capacity as compared to DB method. ILPs have been formulated for IDB and DB methods. The number of variables and constraints required in ILP formulation of IDB method is less as compared to DB method. As a consequence, less computational time is required to solve ILP of IDB method compared to DB method. Computational results show that IDB method is more efficient than DB method concerning spare capacity and computational resources. The number of variables and constraint required in the ILP formulation of DB and IDB method is $O(L.P^2)$. DB and IDB are unable to solve ILP for larger networks having a higher number of cycles(>400).

Chapter 4

Link Pair Method and Single P-cycle Method

In this chapter, we have proposed two different p-cycle based methods: link pair method (LPM) and single p-cycle (SG) method for pre-determined protection from double link failure in an optical network. In the LPM, all the possible pair of links in the optical network is considered, and p-cycles are selected from the non-intersecting set of cycles for each pair of links. We have observed that LPM provides the solution in less time and requires less computational resources as compared to DB and IDB methods described in Chapter 3.

Single p-cycle (SG) method, which uses one p-cycle to protect the working capacity of a link from two simultaneous link failure is also introduced in this chapter. Integer linear programs (ILP) are formulated for the SG method. It has been observed that the SG method provides the solutions for bigger networks with lesser computational resources as compared to the LPM and the methods discussed in the previous chapter.

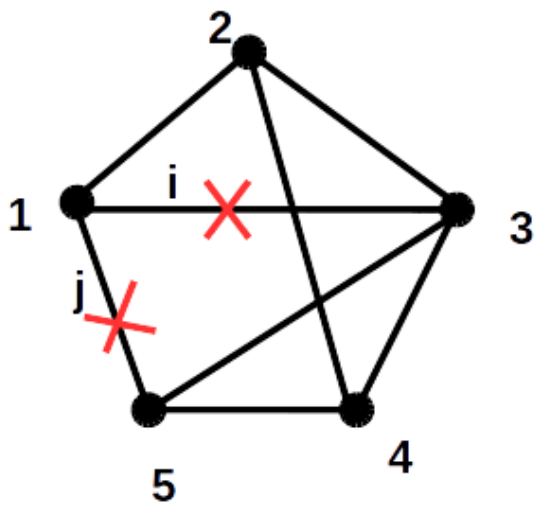


Figure 4.1: Network to illustrate LPM method

4.1 Link Pair Protection Method

In LPM method p-cycles are selected such that on the failure of any two links a sufficient number of p-cycles are available to protect the failed links. We consider each link and take all the possible combinations with the other links of the network. There is $l(l-1)$ possible combination for a network with an l number of links. To ensure the protection of link i, when link i and j fail simultaneously, p-cycles for link i are chosen such that they do not contain link j as an on-cycle link. Similarly, protection of link j is ensured by selecting p-cycles for which link i is not on-cycle. In the network of Fig.4.1 let link i and j fail simultaneously. To protect link i, p-cycles (1-2-3-1), (1-2-4-3-1) and (1-2-4-5-3-1) can be used. To protect link j, p-cycles (1-2-3-5-1), (1-2-4-5-1) and (1-2-3-4-5-1) can be used. Thus when any two links of the network fail, they have a sufficient number of p-cycles to protect the failed links.

The p-cycle which protects the two simultaneously failed links are different in most of the cases. In some cases, the links to be protected from simultaneous failure can share

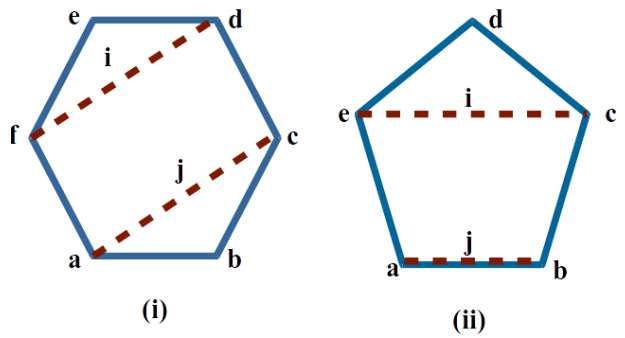


Figure 4.2: Cases when same p-cycle can be shared among two links i and j on simultaneous failure.

the same p-cycle as shown in Fig. 4.2. In Fig. 4.2 (i), links i and j are straddling links on p-cycle (a-b-c-d-e-f-a). Simultaneous failure of links i and j do not affect protection capability of the p-cycle. However, protection capacity of the links cannot be shared by the two links. To protect simultaneous failure of the links, the number of copies of the p-cycle required will be the sum of working capacities on link i and j. In Fig. 4.2 (ii), i and j are straddling and on-cycle links on p-cycle (a-b-c-d-e-a) respectively. If links i and j fail simultaneously, backup path (c-d-e) and (b-c-d-e-a) of p-cycle (a-b-c-d-e-a) can be used to restore the links i and j respectively. Note that for case (ii), the number of copies of the p-cycle required will be the sum of working capacities on links i and j.

4.1.0.1 Integer Linear Program for LPM

The objective of this integer linear program is to find minimum spare capacity required to protect a given network from two simultaneous link failures.

Notations

S=set of spans.

P=set of cycles.

$$x_{i,j,p} = \begin{cases} 1 & \text{if link } i \text{ is on-cycle on p-cycle } p \text{ and link } j \\ & \text{ is not on-cycle on p-cycle } p \\ & \text{or,} \\ & \text{if link } i \text{ is straddling link on p-cycle } p \text{ and link } j \\ & \text{ is on-cycle on p-cycle } p, \\ 2 & \text{if link } i \text{ is straddling link on p-cycle } p \text{ link } j \\ & \text{ is not protected by p-cycle } p, \\ 0 & \text{if link } i \text{ is not protected by p-cycle } p \\ & \text{or,} \\ & \text{link } j \text{ is on-cycle on p-cycle } p. \end{cases}$$

$$\delta_{i,p} = \begin{cases} 1 & \text{if span } i \text{ is on-cycle on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

Variables

s_i =spare capacity on span i.

w_i =working capacity on span i.

c_i =cost of unit capacity of span i.

n_j =number of copies of p-cycle j.

$n_{i,j,p}$ =number of copies of p-cycle p required to protect link i considering link j as second failure.

Minimize:

$$\sum_{i \in S} c_i s_i. \tag{4.1.1}$$

Subject to :

$$\sum_{p \in P} x_{i,j,p} n_{i,j,p} \geq w_i; \qquad \forall i, j \in S; i \neq j. \tag{4.1.2}$$

$$n_p \geq n_{i,j,p}; \quad \forall i, j \in S, \forall p \in P, j \notin p. \tag{4.1.3}$$

$$n_p \geq n_{i,j,p} + n_{j,i,p}; \quad \forall i, j \in S, \forall p \in P : x_{i,j,p} = x_{j,i,p} \neq 0. \tag{4.1.4}$$

$$s_i \geq \sum_{p \in P} n_j \delta_{i,p}; \quad \forall i \in S. \tag{4.1.5}$$

The objective function (4.1.1) minimizes the spare capacity on each link. Constraint (4.1.2) ensures protection of working capacity on link i, on simultaneous failure of links i and j. Constraints (4.1.3) and (4.1.4) select the maximum of the number of copies of p-cycle p required to protect the working capacity of the network. Eqn. 4.1.4 also takes care of the possibility when two links share the same p-cycle as shown in Fig. 4.2. The number of copies of p-cycle shared by the links should be the sum of the capacities of links to be protected. Constraint (4.1.5) ensures that spare capacity on each link is sufficient to form p-cycles.

4.2 Double Link Failure Protection Using a Single P-cycle (SG) Method

Normally, a copy of a p-cycle can protect unit capacity on an on-cycle link and two unit capacity on a straddling link. A straddling link has two alternative paths on the p-cycle for restoration, and this attribute of p-cycle is employed in the SG method to protect the optical network from two simultaneous link failures. In the SG protection method, p-cycles are used to provide protection only to straddling links and on-cycle protection is not used. In case, a p-cycle is shared among multiple straddling links, the number of copies of that p-cycle is taken to be equal to the highest capacity straddling link. The number of copies of p-cycles is equal to the capacity of the straddling link to be protected. If the capacity of the straddling link to be protected is an odd number, then the number of copies of p-cycle is kept one unit capacity higher than the capacity of the straddling link. Even number of copies of p-cycle are required to ensure protection where the capacity of straddling links sharing the p-cycle are equal and an odd number. For example, if the capacity of every straddling link to be protected is three, then the number of copies of the p-cycle should be four. Restoration takes place in two different

ways depending on which two links have failed two straddling links, or a straddling and an on-cycle link. When two straddling links fail simultaneously, the highest capacity straddling link uses half of the capacity of p-cycle, and the other failed link uses the remaining capacity of the p-cycle. When a straddling link and an on-cycle link fail, then the straddling link uses the intact alternative path on p-cycle for restoration. The working paths through the on-cycle links must have been restored as a straddling link by some other p-cycle.

Theorem 4.2.1 *A p-cycle p can protect all the straddling links on it from any two simultaneous link failures, if the number of copies of the p-cycle*

$$n_p \geq \begin{cases} W & \text{if } W \text{ is even,} \\ W+1 & \text{if } W \text{ is odd.} \end{cases}$$

Here, W is the working capacity of the straddling link with maximum capacity, on p-cycle p.

Proof Consider a p-cycle protecting three straddling links $e1$, $e2$ and $e3$ as shown in Fig. 4.3. Assume that $e1$ is the highest capacity straddling link with $w1$ capacity protected by the p-cycle. The number of copy of p-cycle required as per our algorithm to protect network from two link failure will be $w1$ when $w1$ is even, and $w1+1$ when $w1$ is odd. In case of failure of the two straddling links $e1$ and $e2$ as shown in Fig. 4.3 (a), half of the $w1$(or $w1+1$ when $w1$ is odd) copies of p-cycle will be used to restore $e1$. The link $e2$ is restored using remaining half copies of the p-cycle.

In case of the failure of a straddling link and an on-cycle link as shown in Fig. 4.3(b), $w1$ capacity of the intact alternative path on the p-cycle will restore the straddling link $e1$. Link f is restored by some other p-cycle of the network as it must have also been given double fault protection as a straddling link.

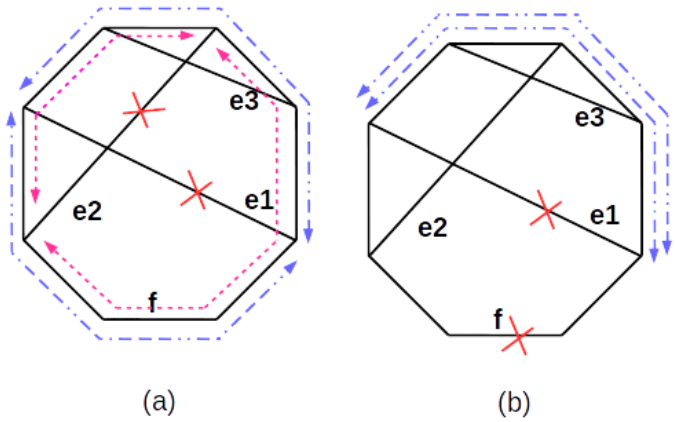


Figure 4.3: Illustration of two link protection by p-cycle in the SG method. (a) Restoration when two straddling link on p-cycle fail. (b) Restoration when straddling link and an on-cycle link on p-cycle fail.

4.2.1 ILP for The SG Method

The objective of this ILP is to find the minimum spare capacity required to protect the optical network from two simultaneous link failures using the proposed protection method. We find the minimum spare capacity needed for single fault protection when only straddling link protection is used. Thereafter, the number of p-cycles needed is merely doubled to provide double fault tolerance.

Notations

S=set of links.

P=set of cycles.

We use $x_{i,p}$ to denote the amount of demand capacity of link i protected by unit capacity of p-cycle p for single fault tolerance with only straddling link protection.

$$x_{i,p} = \begin{cases} 2 & \text{if link } i \text{ is a straddling link on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

We also define,

$$\delta_{i,p} = \begin{cases} 1 & \text{if link } i \text{ is on cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

Variables

s_i =spare capacity on link i.

w_i =working capacity on link i.

c_i=cost of unit capacity of link i.

n_p = number of copies of p-cycle p.

$n_{i,p}$=number of copies of p-cycle p required to protect working capacity of link i in single fault tolerance scenario.

ILP for the SG method is as follows.

Minimize:

$$\sum_{i \in S} c_i s_i. \tag{4.2.1}$$

Subject to :

$$\sum_{p \in P} x_{i,p} n_{i,p} \geq w_i; \qquad \forall i \in S. \tag{4.2.2}$$

$$n_p \geq 2n_{i,p}; \quad \forall i \in S, \forall p \in P. \tag{4.2.3}$$

$$s_i \geq \sum_{p \in P} n_p \delta_{i,p}; \quad \forall i \in S. \tag{4.2.4}$$

$$n_p \geq 0, n_{i,p} \geq 0; \quad \forall i \in S; \forall p \in P. \tag{4.2.5}$$

In equation (4.2.1), the objective function that minimizes the total spare capacity is defined. Constraint (4.2.2) ensures that the protection capacity on p-cycle is sufficient to protect the working capacity on link i as a straddling link under single fault tolerance scenario. Constraint (4.2.3) selects the minimum number of copies of the p-cycles p, required to provide protection to any two straddling links that fail simultaneously. Constraint (4.2.4) ensures that the spare capacity on each link is sufficient to form the p-cycles.

4.3 Complexity Analysis of ILP of LPM and Sg Method

In this section we have computed complexity of number of variables and constraints required in the formulation of LPM and SG method.

4.3.1 Complexity of ILP of LPM method

Number of variables required in the formulation of ILP are $2L + P + L2.P$.
Complexity of number of variables is $O(L^2.P)$.
Number of constraints in the ILP is equal to the sum of number of constraint represented by eqns. 4.1.2 to 4.1.5 is $2L + 2L^2.P$. Complexity of number of constraint is $O(L^2.P)$.

4.3.2 Complexity of ILP of SG method

Number of variables required in the formulation of ILP are $2L + P + L.P$.
Complexity of number of variables is $O(L.P)$.
Number of constraints required in the formulation of ILP of SG method is the sum of number of constraint represented by eqns. 4.2.2 to 4.2.5, and it is given as $2L+2L.P+P$.
Complexity of number of constraint is $O(L.P)$.

4.4 Results and Discussion

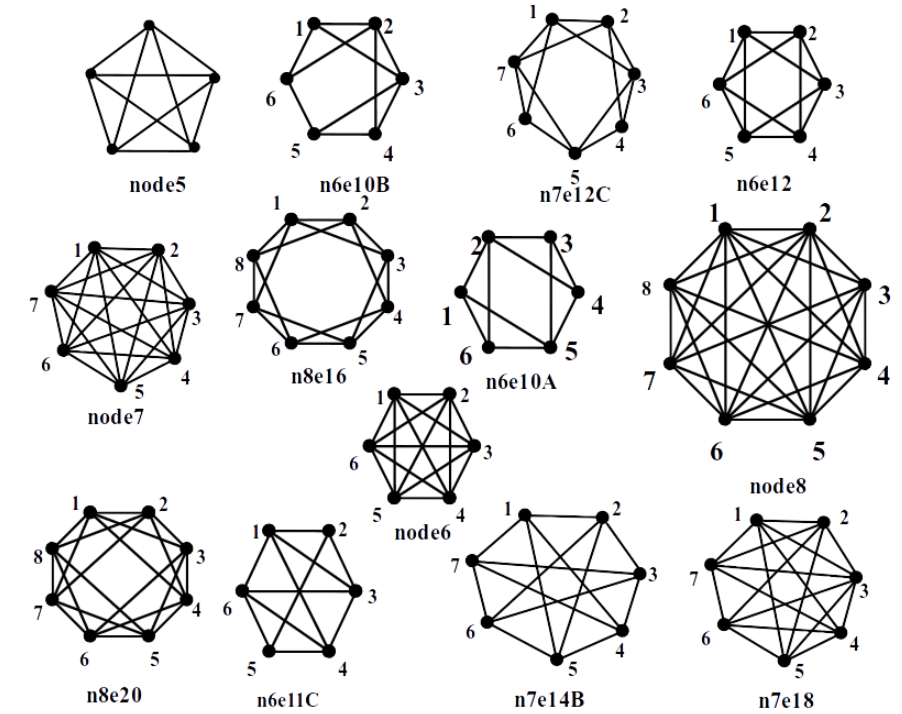
In this section we discuss the performance of LPM and SG, IDB and DB methods (DB and IDB methods have been explained in chapter 3). Simulations have been performed for networks in Fig. 4.4, and result is shown in Table 4.1. A deterministic double

link failure protection method can be implemented only on a 3-connected network, and therefore we have used 3-connected networks in our simulations. Fig. 4.4 (a) are the arbitrary networks with different network parameters. Networks shown in Fig. 4.4 (b) have been taken from [62] [63] [61]. USA long haul, NSFNET and net3 networks have been modified to US LHM, net2m and net3 mod respectively by merge operation explained in Chapter 3(section 3.3). The value of gap is indicated in Table 4.1 only for the network simulations which were stuck to same nonzero value of gap and objective for more than 48hrs.

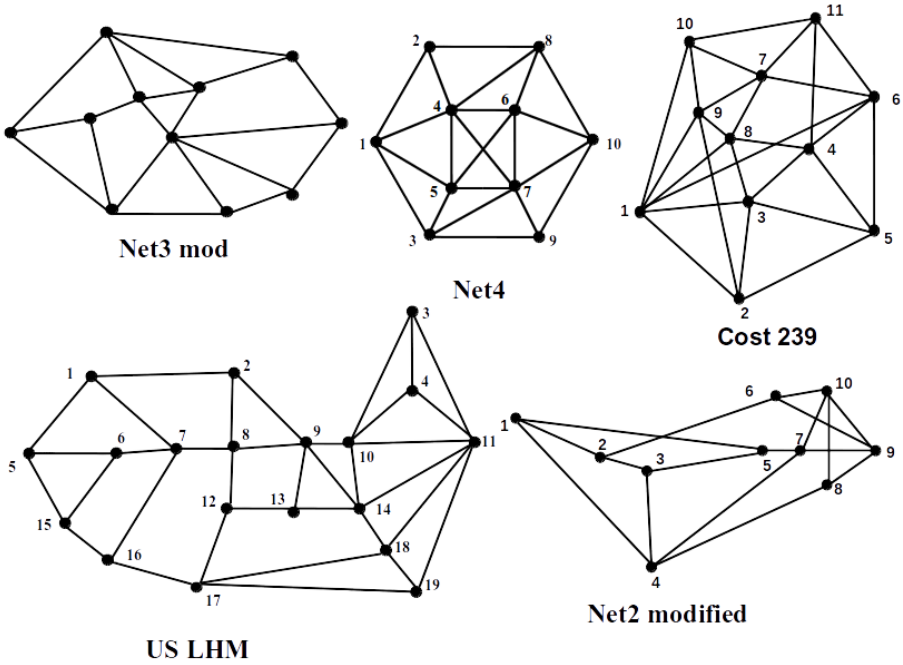
ILP formulation time for LPM method is less compared to DB. ILP formulation complexity of LPM is $O(L^2P)$ while for DB and IDB method $O(LP^2)$. Where L is the number of links in a network, and P is the number of cycles in the network. Less time is required to solve ILP of LPM compared to DB and IDB method. LPM requires less SE (definition 3.4) than DB method for most of the networks. LPM method can compute spare capacity for more extensive networks.

The drawback of LPM is that it uses a different set of p-cycles for a different pair of failed links. The nodes of the failed link have to select and switch to the p-cycles according to the pair of failed links.

In the SG method number of variables and constraints involved in the ILP formulation is $O(L.P)$. Variables and constraints involved in ILP formulation of DB and IDB method is $O(L.P^2)$. Therefore, the complexity of SG method is lower than the DB, IDB and LPM method. One can also note that the complexity of the SG method is same as that of the best known single fault protection method. As evident from the simulation results in Table 4.1, time to solve the ILP is significantly less for the SG method. The results indicate that IDB method gives better SE but fails to provide a solution for large networks. Simulation results show smaller value of SE (Def. 3.4) for most of the networks (see Table 4.1) with the SG method as compared to DB and LPM method.



(a) Arbitrary networks



(b) Optical networks taken from literature

Figure 4.4: Various networks used in simulation

While for average nodal degree higher than 3.6, SG method always gives better SE. Further, it is observed that the SG method has better restoration speed than DB and IDB method. When the first failure occurs, the failed link is restored as a straddling link. In this way, at least half of the copies of p-cycle remain in spare. Restoration path of the first failed link does not require rearrangement if the second failure is also on a straddling link. If the second failure occurs on the on-cycle link of p-cycle, only half of the traffic requires restoration second time. In case of the DB method restoration of the second failure involves the switching of the traffic from the first p-cycle to a different p-cycle. This restoration will be slower as switching action takes place at nodes which may not be the end nodes of the failed link.

Table 4.1: Simulation Results for SG method

Network	Number of cycles	Avg degree	Working capacity	DB method SE	DB method ILP time (in sec)	IDB method SE	IDB method ILP time (in sec)	LPM method SE	LPM method ILP time (in sec)	SG method SE	SG method ILP time (in sec)
n6e10A	22	3.3	40	2.80	0	2.80	0	2.8	0.01	2.45	0
n6e10B	23	3.3	40	2.45	0	2.45	0	2.30	0	1.95	0
n7e12C	39	3.4	60	2.20	0.07	2.12	0	1.93	0.06	1.87	132
net2m	123	3.4	164	3.03	0.07	3.02	0.03	3.46	0.33	3.10	0.01
net3mod	256	3.4	198	2.57	22.54	2.55	8.7	2.56	13.75	2.65	0.03
n6e11C	39	3.6	38	2.63	0.01	2.55	8.68	2.82	0.2	2.63	0
n8e16	179	4	80	1.70	115906	1.24	9570	1.48	87	1.28	14.53
								(gap=0.85%)			
n7e14B	107	4	56	1.89	18487	1.36	144.55	1.82	2.63	1.50	0.01
n6e12	63	4	36	1.78	32.23	1.31	17.4	1.61	0.12	1.50	0.11
node5	37	4	20	1.50	4.12	1	1.17	1	0.11	1.00	0
net4	833	4.4	142	_	*inf	_	*inf	1.77	15178.6	1.65	0.48
cost239	3531	4.7	172	_	*inf	_	*inf	_	*inf	1.06	1745.93
node6	197	5	30	1.00	52594	0.8	323468	0.8	11890	0.80	2.72
						(gap=39.78%)					
n8e20	804	5	72	_	*inf	_	*inf	1.35	78363.9	1.11	0.93
								(gap=2.06%)			
n7e18	459	5.1	48	_	*inf	_	*inf	1.13	729.4	1	234
node7	1172	6	42	_	*inf	_	*inf	0.5	18838.17	0.67	1498.58
node8	8018	7	56	_	*inf	_	*inf	_	*inf	0.57	195681.18
US LHM	5159	3.6	850	_	*inf	_	*inf	2.75	177038	2.90	48.92
								(gap=0.19%)			

*inf means solution could not be achieved by the machine used by us.

4.4.1 Conclusions

In this chapter, we have proposed two spare capacity and computational resource efficient methods: LPM and SG, for double link failure protection in a mesh optical networks. LPM requires less number of variables and constraints as compared to DB and IDB methods. ILP formulation complexity for LPM is $O(L^2.P)$ while for DB and IDB method it is $O(L.P^2)$. Therefore, LPM takes less time to solve ILP and is also able to calculate for larger networks. Spare capacity required by LPM is less compared to DB method. Results suggest that SG method requires less spare capacity as compared to DB and LPM method. SG method is also able to compute the spare capacity of large networks for which DB, IDB, and LPM method fails because the number of variables and constraints required for the SG method is $O(L.P)$ while DB and IDB method need $O(L.P^2)$ variables. IDB method gives better SE for most of the networks. Also, restoration time for SG method after the second failure is better than DB and IDB method which requires re-switching of the first restored path on a different p-cycle after the occurrence of second link failure.

From this study, we can conclude that the spare capacity requirement for deterministic two-link failure protection is less for the SG and IDB methods as compared to the DB and LPM method. Also, ILP of the SG method is more straightforward than any other two-link failure protection method. Consequently, the time required in the ILP formulation and ILP solution is also significantly less for SG method.

Chapter 5

Impact Zone

An optical network which can survive a higher number of simultaneous failures is always desirable. Higher failure protection capability of the network requires a higher number of additional resources. Therefore, researchers have been making efforts to use the redundant resources in an efficient manner to achieve fast recovery from failure conditions at the lowest possible cost. Two link failure protection schemes are desirable due to the high probability of two link failures. p-Cycle is one such shared protection scheme which can provide double fault tolerance in the optical networks. Larger the sharing of p-cycle protection among links, lesser the spare capacity required. If the number of links protected by a p-cycle is large, the network becomes highly unprotected after the occurrence of the first failure.

In this chapter, we investigate the loss of the protection capacity of the network protected by p-cycles after the first failure. We define impact zone which mathematically represents the effect of the link failure on the remaining network protection capacity. Then, various methods have been proposed and analyzed to reduce the impact zone, which leads to increase in double link failure tolerance of the network.

5.1 Mathematical Formulation of Impact Zone

Impact zone analysis of p-cycle based protection scheme can be used to study the vulnerability of network to a second failure after occurrence of the first fault. Protection capacity of a p-cycle is shared among a set of links which can be protected by the p-cycle. Therefore, full protection of only one of these links can be ensured. The other links may lose full or partial protection when the p-cycle gets utilized by the first failure. The affected protection capacity is the protection capacity that is used up by the first failure and is therefore not available to protect the second failure. The protection capacity of the links affected after the failure of a link are:

1. the links which share the same p-cycle for protection as the failed link, and
2. the links which are protected by the p-cycles having the failed link as an on-cycle link.

We can define impact zone of a link as the protection capacity lost by other links due to utilization of p-cycle to protect the failed link. We are considering a network that has 100% single link failure protection. The impact zone has been formulated to quantify the double fault tolerance for a network deterministically protected against single link failure. In this chapter, optical networks are represented by bidirectional graphs. Notations and variables used for an optical network are as follows:

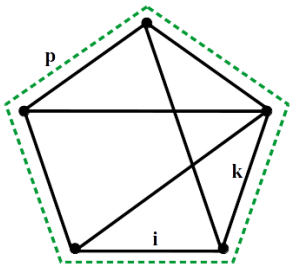
S=set of spans.

P=set of simple cycles.

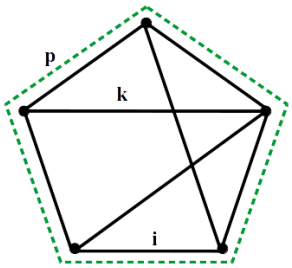
w_i=working capacity on span i.

n_p = number of copies of p-cycle p.

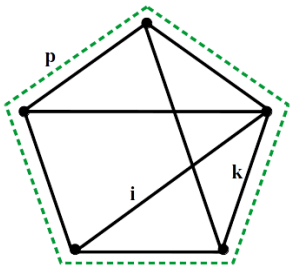
$n_{i,p}$=number of copies of p-cycle p required to protect link i.



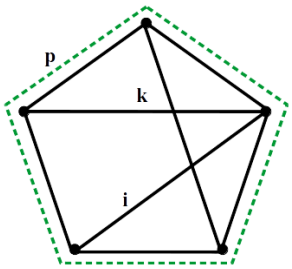
(a) Link i and k are on-cycle on p-cycle p.



(b) Link i is on-cycle and link k is straddling on p-cycle p



(c) Link i is straddling and link k is on-cycle on p-cycle p



(d) Link i and k are straddling on p-cycle p.

Figure 5.1: Illustration of the affected protection capacity provided by the p-cycle p to link k due to failure of the link i.

t_k Overall protection capacity available for link k.

we define $x_{i,p}$ as follows:

$$x_{i,p} = \begin{cases} 1 & \text{if span } i \text{ is on-cycle span on p-cycle } p, \\ 2 & \text{if span } i \text{ is straddling link on p-cycle } p \text{ and} \\ 0 & \text{otherwise.} \end{cases}$$

We define indicator function $I_A(x)$ as follows:

$$I_A(x) = \begin{cases} |x| & \text{if } x < 0, \\ 0 & \text{if } x \geq 0. \end{cases}$$

The impact on the protection capacity depends on whether the failed link and the protected links are on-cycle or straddling links on the p-cycle/p-cycles affected by the failed link. The impact for these cases are formulated below.

1. Link i and other protected link k is on-cycle on p-cycle p as shown in Fig. 5.1(a). The affected protection capacity provided by the p-cycle p to link k due to failure of the link i is given as:

$$I'_{i,k,p} = n_{k,p} \tag{5.1.1}$$

2. Link i is on-cycle and other protected link k is straddling on p-cycle p as shown in Fig. 5.1(b). Impact due to the failure of link i on the protection capacity of link k is given as:

$$I'_{i,k,p} = I_A((n_p - n_{i,p}) - 2n_{k,p}) \tag{5.1.2}$$

3. If link i is straddling link on p-cycle p (Fig. 5.1(c),(d) and $n_{i,p} > 0$,

$$I'_{i,k,p} = I_A(x_{k,p}[(n_p - n_{i,p}) - n_{k,p}]) \tag{5.1.3}$$

Loss of protection capacity of link k due to failure of link i is

$$I'_{i,k} = \sum_{p \in P} I'_{i,k,p} \tag{5.1.4}$$

The remaining capacity to protect link k after failure of link i is $t_k - I'_{i,k}$. Since we have considered deterministic single link protection $t_k \geq w_k$. If $t_k - I'_{i,k} \geq w_k$ then, link i gets full protection even after failure of link i. But, if $t_k - I'_{i,k} < w_k$ then, $w_k - (t_k - I'_{i,k})$ capacity of link k remains unprotected in case of failure of link i. The impact zone of link i, I_i can be written as:

$$I_i = \sum_{\substack{k \in S \\ I'_{i,k} \neq 0}} I_A(t_k - I'_{i,k} - w_k) \tag{5.1.5}$$

5.1.1 Example to Calculate Impact Zone

Consider the network shown in Fig 5.2. We calculate impact zone for link i in Fig. 5.2. Let p(1-2-3-4-5-1), q(1-2-3-4-1) and r(1-4-5-1) be the p-cycles associated with link i which protect links (e_1, e_2, i),(e_3, e_6, i) and (e_4, e_5) respectively. When link i fails, p-cycles p and q will be used to protect the link i. Links e_1-e_6 will lose protection fully or partially depending on the number of copies of the p-cycles p and q used to restore the link i. After using protection for link i, the remaining copies of p-cycle p will be $n_p - n_{i,p}$. Protection lost by e_1 and e_2 will be $n_{e_1,p} - (n_p - n_{i,p})$ and $n_{e_2,p} - (n_p - n_{i,p})$ respectively. Link e_3 is on-cycle on p-cycle q therefore, $n_{e_3,q}$ number of protection capacity of e_3 will be lost. Link e_6 is a straddling link on p-cycle q. P-cycle q protects $2n_{e_6,q}$ working capacity of link e_6. The protection lost by e_6 will be $2n_{e_6,q} - (n_q - n_{i,q})$. Links e_4 and e_5 are on-cycle on p-cycle r and will, therefore, lose protection for $n_{e_4,r}$ and $n_{e_5,r}$ respectively. The impact zone of link i will be the sum of the protection capacity lost by links e_1-e_6 and will be given by the following equation.

$$I_i = n_{e_1,p} + n_{e_2,p} - 2(n_p - n_{i,p}) + n_{e_3,q} + 2n_{e_6,q} - (n_q - n_{i,q}) + n_{e_4,r} + n_{e_5,r}. \quad (5.1.6)$$

5.2 Improving Double Fault Tolerance

An optical network protected for single link failure will have some inherent double link failure tolerance. Reducing impact zone of the network results in increase in its double fault tolerance capability. The increase in fault tolerance in the optical network comes at the expense of the rise in redundant capacity. The reduction of impact zone will increase the spare capacity and hence cost of network protection. In the following subsection,

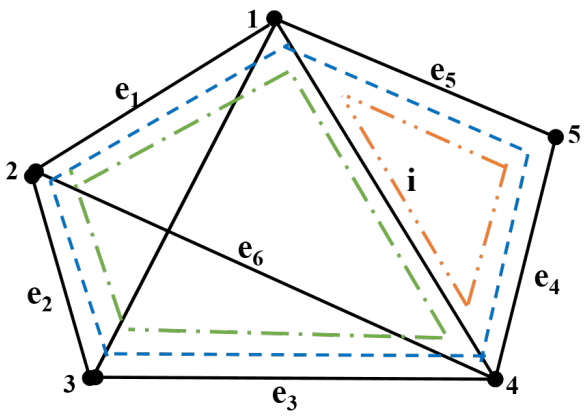


Figure 5.2: Example of a network for calculating Impact zone of link i.

we state an ILP for single link failure protection [21] where additional constraints have been incorporated to reduce its impact zone thereby increasing its tolerance to double link failure i.e. failure of one more link after the first link.

5.2.1 ILP for Single Link Protection

In [21], Grover *et al* have described deterministic single-link protection scheme using p-cycles. In this section we state and describe an ILP for single link protection (SLP) [21] with additional variables and constraints required to calculate impact zone in an optical network. The SLP described is further used in the subsequent section as a building block to improve double fault tolerance by adding more constraints.

Notations

In addition to the notations defined in section 2, we define following notation to formulate the ILP for single link protection in the optical network.

c_k=cost of unit capacity of span k.

s_k=spare capacity on span k.

$$\delta_{i,p} = \begin{cases} 1 & \text{if span } i \text{ is on-cycle on p-cycle } p, \\ 0 & \text{otherwise.} \end{cases}$$

Minimize:

$$\sum_{i \in S} c_i s_i. \tag{5.2.1}$$

Subject to:

$$\sum_{\forall p \in P} x_{i,p}.n_{i,p} \geq w_i; \qquad \forall i \in S. \tag{5.2.2}$$

$$n_p \geq n_{i,p}; \quad \forall p \in P, i \in S. \tag{5.2.3}$$

$$s_i \geq \sum_{p \in P} n_p \delta_{i,p}; \qquad \forall i \in S. \tag{5.2.4}$$

$$n_p \geq 0, n_{i,p} \geq 0; \quad \forall i \in S, \forall p \in P. \tag{5.2.5}$$

The objective function given by equation 5.2.1 minimizes the total spare capacity on each link of the optical network. Constraint 5.2.2 ensures that the number of copies of the p-cycles are sufficient to protect the working capacity on all the links. Constraint 5.2.3 selects the number of copies of p-cycle required to protect the maximum working capacity link by that p-cycle. Constraint 5.2.4 ensures that the spare capacity on each link is sufficient to form p-cycles. It should be noted that, variable $n_{i,p}$ is required to calculate the impact zone. Therefore, variable $n_{i,p}$ and constraint 5.2.3 are added to the SLP.

5.2.2 Minimizing Impact Zone

Solution of the ILP given by eqns. 5.2.1-5.2.5 for a given optical network provides optimum spare capacity and p-cycles required to protect the network from a single link

failure. The impact zone for the links in the network is computed using the variables obtain by solving the SLP (Eqns. 5.2.1-5.2.5) in eqns. 5.1.1-5.1.5. The value of the impact zone depends on the variables which are obtained from the solution of the ILP. Lower value of impact zone indicates better double link failure tolerance.

We try to limit the value of impact zone by adding limiting-constraints to the ILP of SLP (Eqns. 5.2.1-5.2.5). The limiting-constraints control the variables involved in the impact zone. This approach reduces the impact zone by reducing the sharing of p-cycle among links. Reducing the sharing of p-cycle among links, however, will increase the spare capacity. In the following subsection, we will study the effect of adding limiting constraints on the impact zone and the spare capacity.

5.2.2.1 Limiting-constraint 1

We add limiting-constraint 1 (L1) given by eqn., 5.2.6 to reduce the value of the impact zone. The left hand side of L1 contains all the variables associated with link i which can affect the protection capacity of other links.

$$\begin{aligned}\sum_{p\in P}\sum_{\substack{j\in S\\ j\neq i\\ x_{i,p}=1\\ x_{j,p}=1}} n_{j,p} + \sum_{p\in P}\sum_{\substack{j\in S\\ j\neq i\\ x_{i,p}=1\\ x_{j,p}=2}} [n_{j,p}-(n_p-n_{i,p})] + \sum_{p\in P}\sum_{\substack{j\in S\\ j\neq i\\ x_{i,p}=2\\ x_{j,p}=2}} 2[n_{j,p}-(n_p-n_{i,p})]\\ + \sum_{p\in P}\sum_{\substack{j\in S\\ j\neq i\\ x_{i,p}=2\\ x_{j,p}=1}} [n_{j,p}-(n_p-n_{i,p})] \leq K; \qquad \forall i\in S.\end{aligned} \tag{5.2.6}$$

Here, K is a constant. For sufficiently large value of K the solution of the ILP converges to single link protection ILP. Therefore, the impact zone is also same for the large value of K. Impact zone decreases as we reduce the value of K.

5.2.2.2 Limiting-constraint 2

Instead of limiting constraint-1, we can add limiting-constraint 2 (L2) given by eqn. 5.2.7 to the ILP of single link protection eqns., 5.2.1-5.2.5.

$$n_p \geq \sum_{\substack{i \in S \\ x_{i,p} \neq 0}} n_{i,p}; \qquad \forall p \in P. \tag{5.2.7}$$

Eqn. 5.2.3 along with eqn. 5.2.7 limits the number of links which can share a p-cycle. The number of links sharing a p-cycle is less due to imposed limit as compared to normal single link protection ILP. The impact zone reduces by adding constraint 5.2.7 and consequently the required spare capacity for the network protection increases.

5.2.2.3 Limiting-constraint 3

We add the following additional limiting constraints-3 represented by (L3) eqns. 5.2.8-5.2.11 to the ILP given by eqn. 5.2.1-5.2.5. L3 ensures that each p-cycle protects only one link. Thus, there is no sharing of p-cycles among links.

We define $a_{i,p}$ as a binary variable associated with link i and p-cycle p. It indicates if p-cycle p is protecting link i ($a_{i,p} = 1$) or not ($a_{i,p} = 0$). M is a sufficiently large positive number($M >> \sum_{i \in S} w_i$).

$$a_{i,p} \geq \frac{n_{i,p}}{M} \quad \forall i \in S. \tag{5.2.8}$$

$$a_{i,p} \leq 1 \quad \forall i \in S. \tag{5.2.9}$$

$$\sum_{\substack{\forall i \in S \\ x_{i,p} \neq 0}} a_{i,p} \leq 1 \qquad \forall p \in P. \tag{5.2.10}$$

$$a_{i,p} \geq 0 \qquad \forall i \in S, \forall p \in P. \tag{5.2.11}$$

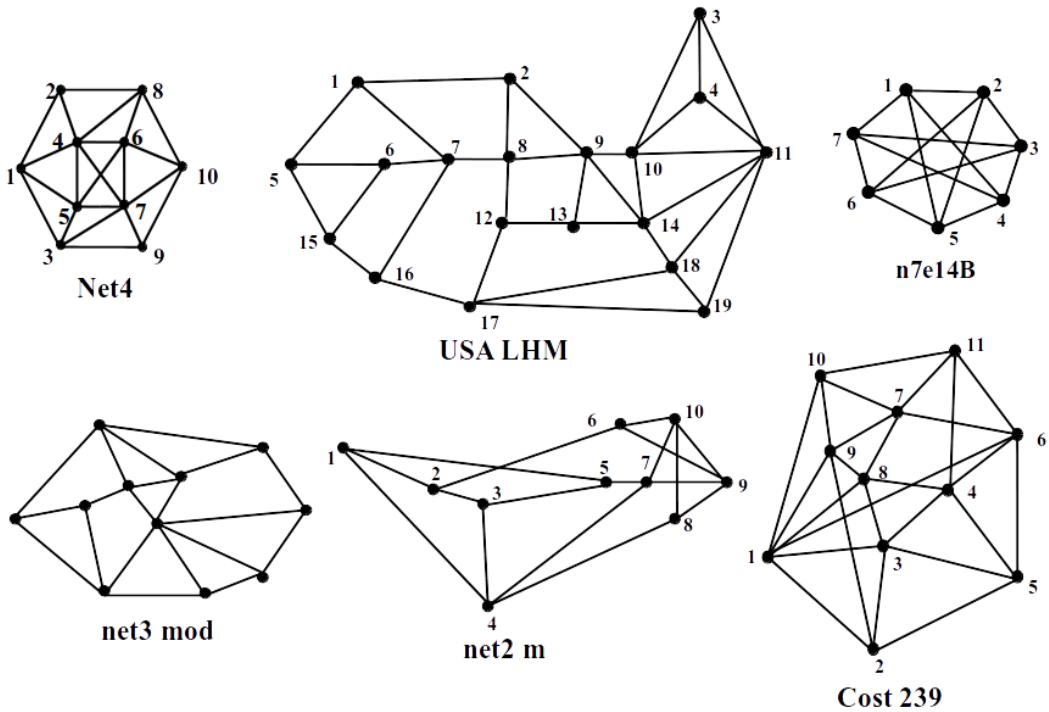


Figure 5.3: Network graphs used for simulation.

Constraints 5.2.8 and 5.2.9 ensure that the variable $a_{i,p}$ takes binary value (0 or 1). Constraint 5.2.10 ensures that each p-cycle protects only one link. Constraint 5.2.11 ensures that $a_{i,p}$ takes only positive value.

5.3 Results and Discussion

In this section, we analyzed the effect of limiting-constraints L1, L2 and L3 independently in terms of spare capacity and impact zone. Simulation is performed for the networks shown in Fig. 5.3. Scilab 5.5 has been used for the ILP formulation. ILOG CPLEX 9 has been used to solve the ILP on AMD Opteron(tm) 1.8 GHz CPU.

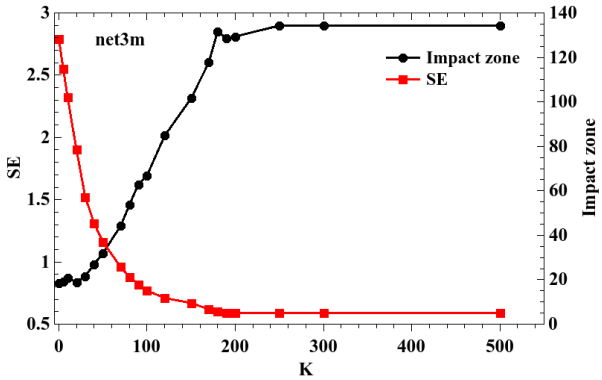
Table 5.1: Simulation Results

Network	SLP		L1(K=0)		L1(K=max)		L2		L3	
	SE	Impact Zone	SE	Impact Zone	SE	Impact Zone	SE	Impact Zone	SE	Impact Zone
net3mod	0.59	155.5	2.79	18.45	0.59	134.3	2.85	0	2.85	0
net2m	0.8	106	3.62	21.5	0.8	80.1	3.50	1.2	3.59	0
n7e14B	0.54	39	2.18	7.9	0.54	32	2.29	0	2.29	0
Net4	0.47	106.8	2.06	15.5	0.47	88.7	2.34	0.2	2.36	0
USA LHM	0.71	532	3.36	51.7	0.71	414	3.22	3.3	3.24	0
cost239	0.43	106	1.90	17.8	0.43	99.9	2.31	0.08	2.31	0

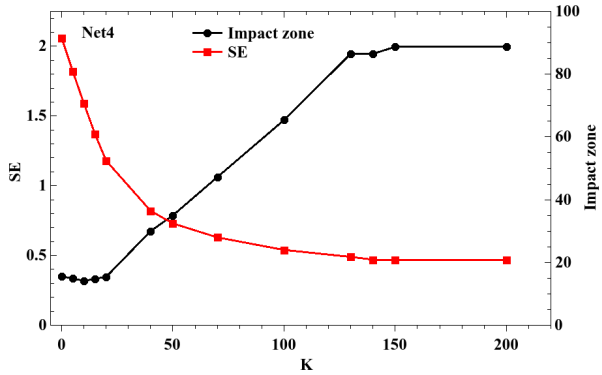
5.3.1 Performance of Limiting Constraints L1, L2 and L3

Single link protection ILP eqn. 5.2.1-5.2.5 with L1 (eqn. 5.2.6) is solved for different values of K. As hypothesized, the value of impact zone increase, while SE decreases with increasing K (Fig. 5.4). There is a trade off between SE (please refer to spare capacity efficiency defined in chapter 3 eqn. 3.4.1) and impact zone, which is expected because lower value of impact zone implies greater fault tolerance capability which in turn requires high spare capacity. The value of K can be chosen according to the desired value of SE and impact zone. It should be noted that the value of impact zone does not reduce to zero for $K = 0$. Eqn. 5.2.6 gives limited control over impact zone.

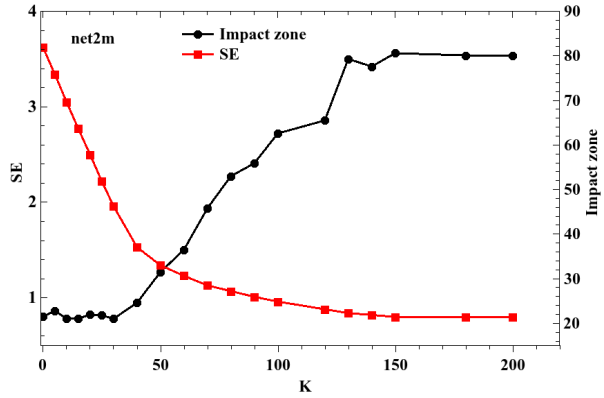
Various protection methods earlier described in section 3.2, SLP, SLP with L1, SLP with L2, SLP with L3 are compared in Fig. 5.5 and table 5.1. In Fig. 5.5 $L1\_K0$ represents the result with L1 and $K = 0$ while, $L1\_Km$ represents the result with L1 and value of K for which SE and impact zone for the given network saturates. Limiting constraints L2 and L3 reduce the overlapping protection capability of p-cycles and therefore, impact zone is also reduced for these constraints. Results in Table 5.1 show the existence of low value of impact zone for L2, while for L3 impact zone is zero



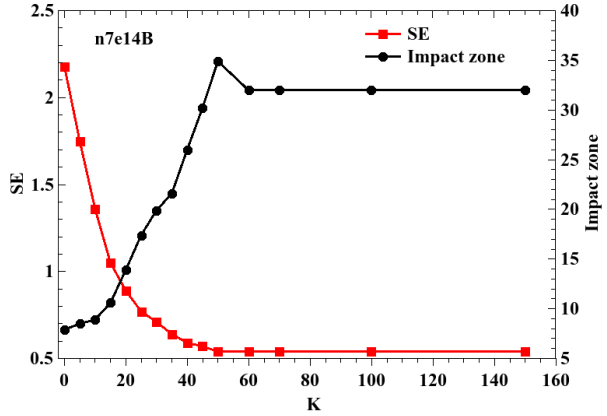
(a) net3m



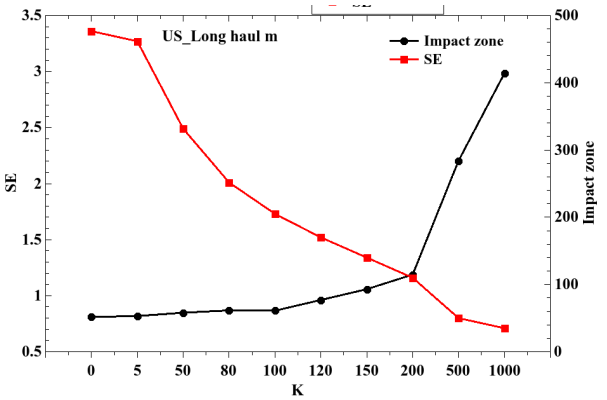
(b) net4



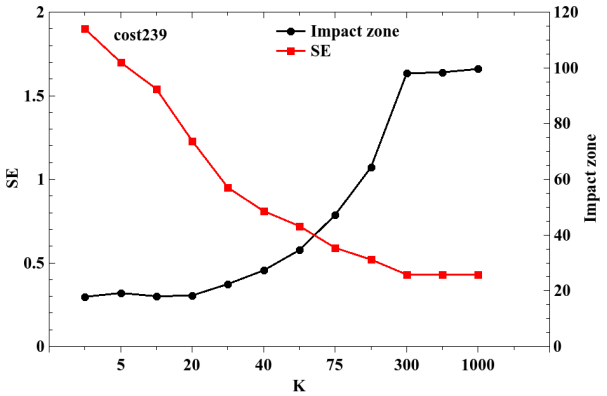
(c) net2m



(d) n7e14B

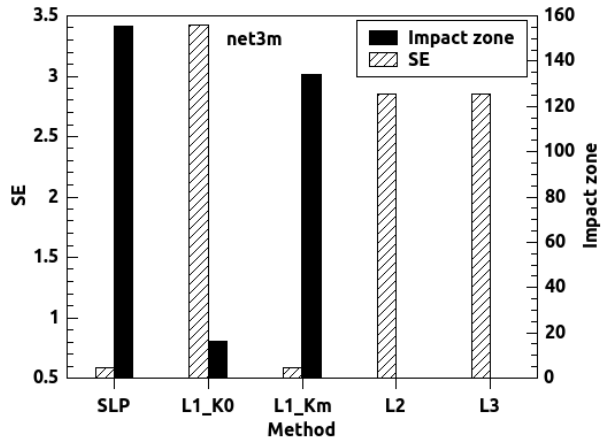


(e) US Long Haul m

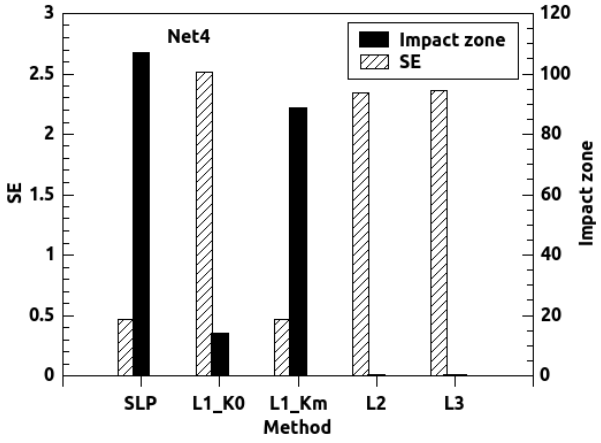


(f) cost239

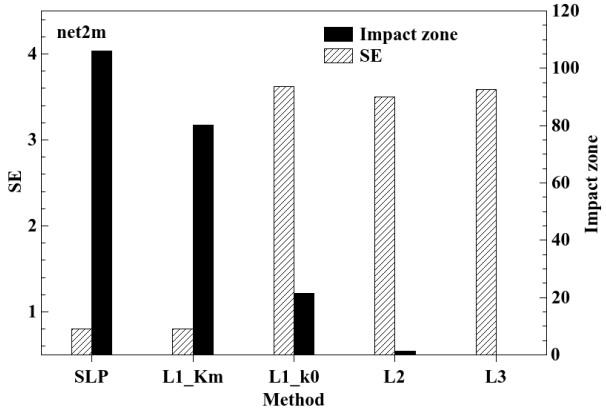
Figure 5.4: Effect of variation of K on impact zone and SE for various networks with constraint L1



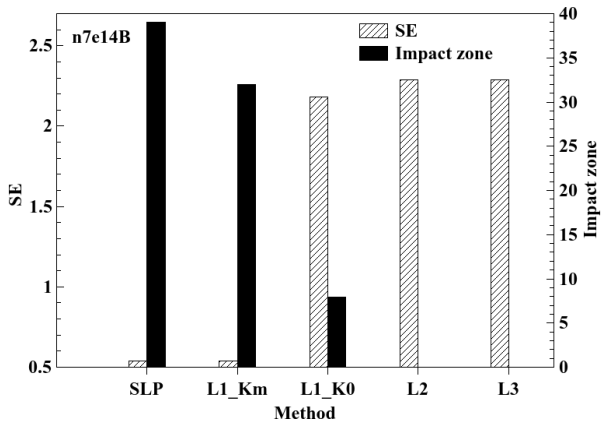
(a) net3m



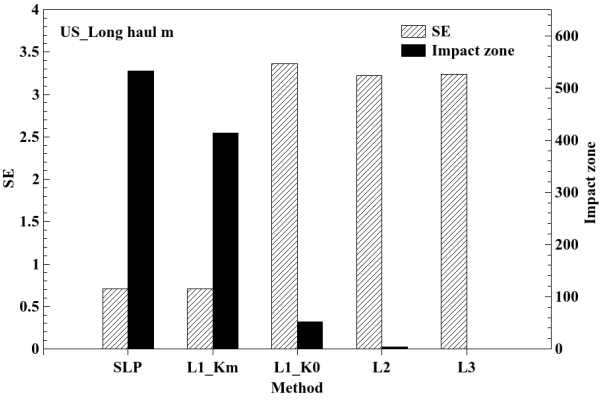
(b) net4



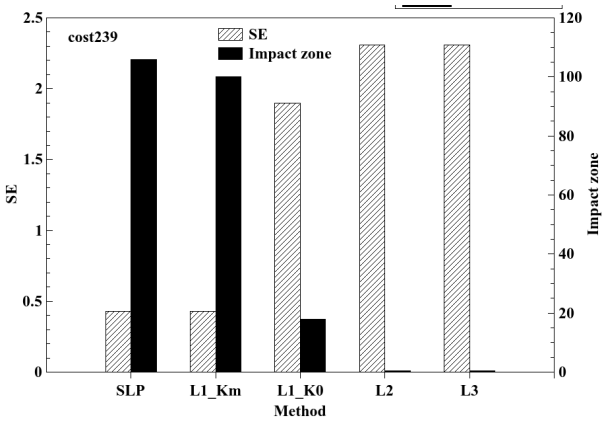
(c) net2m



(d) n7e14B



(e) US Long Haul m



(f) cost239

Figure 5.5: Effect of different limiting constraints on Impact zone and SE

for all the networks studied. The value of SE is higher with L1, L2 and L3 as compared to SLP. SE and impact zone are comparable for L2 and L3. Also, L2 and L3 gives better double link failure tolerance than L1 and SLP. L2 and L3 gives higher value of SE which is a disadvantage. However impact zone is almost negligible for L2 and L3 and could be useful for the networks that needs higher double fault tolerance. A lower value of impact zone implies higher protection capability of the network. Higher protection capability in a network requires the more spare capacity. Therefore lowering the value of impact zone will always increase the needed spare capacity. The cost involved and protection provisioned will be the deciding factor for the amount of impact zone and spare capacity.

Impact zone should also be considered along-with SE while designing an optical network. The methods can be chosen depending on the requirement of the network.

5.4 Conclusions

Impact zone is a measure of the protection lost by network after a failure and corresponding restoration. We have proposed this measure for the first time to the best of our knowledge. In this chapter, double link failure tolerance of the networks has been improved by few proposed techniques to reduce the impact zone. Improvement in double fault tolerance comes at the expense of the increase in spare capacity. Various limiting constraints are added to single fault protection ILP to reduce the impact zone in order to improve the double link failure tolerance of the network. The value of impact zone can be adjusted within a certain range by varying the K using limiting constraint L1. Limiting constraints L2 and L3 reduce the impact zone by limiting the sharing of p-cycles among links. We observed that L2 and L3 give better double link failure

tolerance as compared to L1 with the increase in SE. Limiting constraint L1 can be used to tune the desired value of impact zone and SE. L1 does not provide the lowest possible value of impact zone. L2 and L3 give negligible impact zone but with higher value of SE.

There is a trade-off between impact zone and SE. Both SE and impact zone should be considered while designing a survivable optical network. Choice of method might depend on the design requirement of the network.

Chapter 6

Conclusions and Future works

Survivability is an essential aspect of optical network design. A network which can survive any failure is desirable. Protection schemes are required to provide survivability to the optical networks. The efficacy of a protection scheme depends on how much redundant capacity it utilizes, the speed of recovery and the types of failures it can protect. Generally, protection schemes are devised for the protection of most probable failures.

6.1 Conclusions

In optical networks, fiber cuts are the most prominent cause of link failures. Single link failure being most common and frequent has been extensively studied. Double link failure with overlapping protection resources are frequent enough in large optical networks and therefore are of interest and thus have been studied in the literature. Designing an optical network for double link protection has the following problems.

1. Double link failure protection requires large number of redundant resources.

2. Optimization problem for double link failure protection involves large number of variables and constraints therefore its optimum capacity computation either fails or takes days to solve for large networks.

There are various schemes proposed in the literature; most of them provide full single link protection with an attempt to increase the double link protection. The heuristic algorithms that are proposed, lack in the speed of recovery. Few other schemes proposed in the literature which provide full protection either lack speed or are able to optimize resources for only very small networks. Various double link protection methods proposed in this thesis are able to address these problems to some extent. We have chosen P-cycle protection scheme in this thesis which provides fast recovery just like ring protection scheme and are spare capacity efficient like mesh protection.

We have proposed IDB method for double link protection in chapter 3, which is an improvement over DB method. The IDB method is more capacity efficient than DB method. It has been shown analytically as well by simulations that the IDB method require less spare capacity, and less number of variables and constraints as compared to DB method.

Two different deterministic double link protection methods, LPM and SG methods, have been proposed in chapter 4. ILP formulation complexity has been found to be less for LPM method as compared to DB and IDB method. ILP formulation complexity for DB and IDB methods is $O(L.P^2)$ while for LPM method complexity is $O(L^2.P)$. Here, L is the number of links, and P is the number of cycles for a network $G(N, L)$ with N number of nodes and L number of links. The number of variables and constraints are greatly reduced in LPM method compared to IDB and DB method, consequently reducing the ILP solution time. We have also observed that SE value is lower for the networks with a higher average nodal degree.

SG method which uses a single p-cycle to protect a link from two simultaneous failure has also been proposed. The number of constraints and variables required by SG method is even less than all the other methods proposed in this thesis. It has also simplified the ILP formulation further. The complexity of ILP formulation for SG method is $O(L.P)$, which is the least among all the methods. Spare capacity is less for SG method for most of the networks studied in this thesis. Again the value of SE is found to reduce with increase in the average nodal degree of the network. We have been able to get optimum solution for bigger networks like Net4, cost239, node8 (a complete graph with the number of nodes equal to 8) for which optimum solution with all other deterministic double link protection methods could not be computed.

A new parameter called impact zone has been proposed to analyze double fault tolerance of an optical network after occurrence and restoration of single link failure. Impact zone effectively quantifies the loss of protection by the network after failure. We have further used the concept of impact zone in improving the double fault protection capability of a single link protected network. Various limiting constraints are added to single link protection ILP to improve double link protection of the networks. Limiting constraint-1 (L1) with a constant K is added to single link protection ILP. The value of impact zone can be controlled by varying K. Impact zone tends to increase with the value of K while SE decreases. A low value of impact zone and SE is desirable. Since there is a trade-off between SE and impact zone $L1$, K can be used to tune SE and impact zone. Limiting constraint-2 (L2) and limiting constraint-3 (L3) were added to single link protection ILP to reduce the sharing of p-cycle among links. The impact zone has been significantly reduced for both the $L2$ and $L3$ constraints for all the networks in this thesis.

6.2 Future Scopes

There are many problems worth investigating which were identified while pursuing this research work. Some of them are listed below:

1. Joint capacity optimization of working and spare capacity can be studied to make network further capacity efficient.

2. In all the double link failure protection methods described in this thesis, it was assumed that the nodes have 100 % wavelength convertibility. The methods described can be investigated on the network with no or partial wavelength convertibility.

3. The methods described in this thesis are implemented on the DWDM network. It would be interesting to investigate the methods described in the thesis on elastic optical networks and mixed line rate networks.

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List of Publications

1. **Pallavi Athe** and Y. N. Singh, "Double Link Failure Protection using a Single P-cycle," *Optical Switching and Networking* (submitted).

2. **Pallavi Athe** and Y. N. Singh, "Improved Double Cycle and Link Pair Methods for Two-Link Failure Protection," in *Photonic Network Communications* (submitted).

3. **Pallavi Athe** and Y. N. Singh, "Impact Zone Analysis of p-Cycle," in *Journal of Optical Communications and Networking* (submitted).