PROACTIVE CONNECTION RECOVERY STRATEGIES FOR SURVIVABLE ELASTIC OPTICAL NETWORKS

Thesis submitted in fulfillment of the requirement for the degree of

Doctor of Philosophy

By

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April 2021

Dedicated to my family

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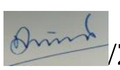
DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled "**Proactive Connection Recovery Strategies for Survivable Elastic Optical Networks**" submitted at the **Jaypee University of Information Technology, Waknaghat, Solan (HP)**, **India** is an authentic record of my work carried out under the supervision of **Dr. Rajiv Kumar and Dr. Neeru Sharma**. I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. thesis.

/27/04/2021

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled "**Proactive Connection Recovery Strategies for Survivable Elastic Optical Networks**" submitted by Dinesh Kumar, at the **Jaypee University of Information Technology, Waknaghat, Solan (HP), India** is a bonafide record of his original work carried out under my supervision. This work has not been submitted elsewhere for any other degree or diploma.

1) /27/04/2021 2) /27/04/2021

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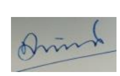 27/04/2021

Dinesh Kumar

ABSTRACT

Optical fiber provides very high bandwidth, offers a high-speed network, and carries vast information. By using dense wavelength division multiplexing (DWDM) technology a large amount of data can be transmitted simultaneously. The optical fiber network is the backbone for internet traffic worldwide. In the last few years, internet traffic increases continuously due to the more use of live streaming and social sites. To accommodate such high traffic demand the more bandwidth is required. The elastic optical network (EON) is an emerging solution to meet the future higher bandwidth requirement. The EON can provide a higher data rate. The link and node failure in the optical network causes huge revenue and data loss. The survivability of high-speed networks is very essential. For the survivability of EON, a backup path is reserved in advance or searched dynamically after the failure occurred in the network. Both these recovery strategies required a large backup capacity. In this thesis, we proposed four different types of survivability schemes for a single and dual-link failure in the optical network. Initially, we proposed a halfway signaling exchange shared path protection (HSE-SPP), a pre-assigned intermediate node on the backup route is chosen for signaling exchange. When the connection fails, source and destination nodes simultaneously generate backup connection setup messages to the pre-assigned intermediate node on the reserved backup route. Consequently, connection recovery time by applying HSE-SPP becomes very low.

As the size of the network increased the possibility of the double-link failure and node failure also increases. For dual-link failure, we implemented a parallel cross-connection backup recovery scheme. Our proposed survivable scheme has lower bandwidth blocking probability (BBP), minimum bandwidth provisioning ratio (BPR), and fast connection recovery time, than existing dedicated path protection (DPP), and shared path protection (SPP). Simulation is performed for ARPANET, COST239, and NSFNET topologies. The main purpose of the whole thesis is to provide survivability against failure in the elastic optical network.

The first chapter provides a brief introduction of the optical communication network. In the second chapter different types of survivability schemes have been discussed. The third chapter of the thesis presents the proposed half way signaling exchange-shared path protection (HSE-SPP) for a single link failure in elastic optical networks. In the fourth and fifth chapters, we proposed a path and link-based recovery scheme for a failure in elastic optical networks. Chapter

sixth shows a proposed intermediate node cross-connect backup for shared path protection (INCB-SPP) for a double link failure in the elastic optical network.

Finally, in the seventh chapter, the conclusion and future scope have been presented.

LIST OF ACRONYMS & ABBREVIATION

Acronyms & Abbreviation

ADP	Aware differentiated protection
ADCC	Automatic double cycle cover
AFRO	After failure repair optimization
ARPANET	Advanced Research Project Agency Network
ATM	Asynchronous transfer mode
APS	Automatic protection switching
BBP	Bandwidth blocking probability
BVT	Bandwidth variable transponder
BPR	Bandwidth provisioning ratio
BROR	Backup resource overbuild ratio
BW	Bandwidth
BSHR	Bidirectional self-healing ring
BVT	Bandwidth variable transponder
OXC	Optical cross-connect
DARPA	Defense advanced research projects agency
DCF	Dispersion compensated fiber
DP	Dedicated protection
DLP	Dedicated link protection
DLF	Dual-link failure
DPP	Dedicated path protection

DWDM	Dense wavelength division multiplexing
EMI	Electromagnetic interference
EON	Elastic optical network
FIPP	Failure independent path protection
FS	Frequency slot
FP	Fixed path
FON	Flexible optical network
HSE-SPP	Halfway signaling exchange shared path protection
HSMR	Hybrid single and multipath routing
HAFA	Hybrid adaptive frequency assignment
HDVS	High definition video streaming
HOS	Hybrid optical switching
ILD	Injection laser diode
ILP	Integer linear programming
IP	Internet protocol
INCB-SPP	Intermediate node cross-connect backup for shared path protection
MILP	Mixed integer linear programming
MPCS	Message processing for connection setup
MRSA	Multipath routing and spectrum allocation
MPP	Multipath protection
MPAK	Message processing for acknowledgment
MFSB	Minimum free spectrum block consumption
NEPC	Node encircling p-cycle

OADM	Optical add-drop multiplexing
OAMP	Operation administration maintenance and provisioning
ODU	Optical data unit
OSPM	Optimal shared protection mapping
OPC	Online path computation
OTN	Optical telecommunication network
PDH	Plesiochronous digital hierarchy
PT	Propagation time
PLP	Proposed link protection
PBR	Primary backup route
PON	Passive optical network
PSTN	Public switched telephone network
QoS	Quality of Services
RO	Resource overbuild
ROADM	Reconfigurable optical add-drop multiplexer
RSA	Routing and spectrum assignment
RT	Recovery time
RTC	Recovery time constraint
RTSPP	Recovery time for shared path protection
RTDPP	Recovery time for dedicated path protection
RTHSE-SPP	Recovery time halfway signaling exchange shared path protection
SDM	Space division multiplexing
SHR	Self-healing ring

SLICE	Spectrum sliced elastic optical path
SBPP	Shared backup path protection
SDN	Software-defined network
SLP	Shared link protection
SPP	Shared path protection
SPPMPR	Single path provisioning multi-path recovery
SONET	Synchronous optical networking
SDH	Synchronous digital hierarchy
TBVT	Tunable bandwidth variable transponder
TACK	Total acknowledgment time
TBFT	Tie based fault tolerance strategy
TCS	Total connection setup time
TCP	Transmission Control Protocol
TDM	Time-division multiplexing
TS	Tabu search
USHR	Unidirectional self-healing ring
VON	Virtual optical network
WDM	Wavelength division multiplexer
WMD	Weapons of mass destruction

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CHAPTER 1

1. INTRODUCTION

Communication has the ability to exchange information, knowledge, and experience with each other. The exchange of information through any medium leads to society's development. Communication plays an important role in mankind's development worldwide. The higher communication speed resulting in more development rate.

In the beginning, communication begun with drums and smoke. In early 1790 the first semaphore comes into view in Europe and remained up to 1830 till electrical communication started. Modern telecommunication has started after the invention of the Morse telegraph in 1840 [1]. The telegraph expanded globally for the use of daily lives, in the government sector, and for business purposes. The exponential growth in the electrical sector provided a background to the success of the telegraph and telephone. In early 1876 [2] for the invention of the telephone Alexander Graham Bell received U. S. patent. In the beginning, iron wires are used for telephone communication and the distance is restricted up to 100 miles only. The stepping switch has been invented in 1891 by Almon Brown Strowger [3], which leads to the automation of telephone switching. The coaxial cable comes into sight in 1936, and provides high bandwidth for the transmission of audio and video signals for longer distances. The swing from analog to digital signals makes a huge change in the communication industry. Anything (voice, data, and image) that are converted into numbers can be transmitted by digital communication. Digital switches are flexible in operation and the design of the networks.

Later, the internet formed a computer network globally. The numbers of computers are connected to each other by PSTN (Public switched telephone network) to form the business, research, and academic computing network. The optical fiber provides a backbone network to the internet globally for regional and long-distance communication. The COST239 is an ultra-high-capacity optical transmission network of

Europe. It connects major cities within Europe. The other network is NSFNET in the US (United States). This is also known as the National science foundation network and is used to promote advanced research and academic networking in the US. NSFNET connecting supercomputing centers in the US. The other network is also funded by the US defense that is the Advanced Research Project Agency Network (ARPANET) is the first internet prototype. The US Defense Advanced Research Projects Agency, (DARPA) formed two protocols-Internet Protocol (IP) and Transmission Control Protocol (TCP), which is used for the transmission of various information in all the systems.

The current telecommunication system is based on the optical transmission of the signal through an optical fiber. The optical fiber offers very high bandwidth, immunity to electromagnetic interference (EMI), light in weight, less signal attenuation, optical fiber is more flexible, higher signal carrying capacity, and provides 100% security for the transmission of information.

The optical fiber networking is briefly explained in the following sections.

1.1 Optical Networking

Presently, the whole world is connected through the internet. The optical network is used as a backbone for the internet. The optical network is the interconnection between the nodes, these nodes are connected via the medium known as an optical fiber. All the nodes are able to multiplex and de-multiplexing the signal at the transmitter and receiver end simultaneously.

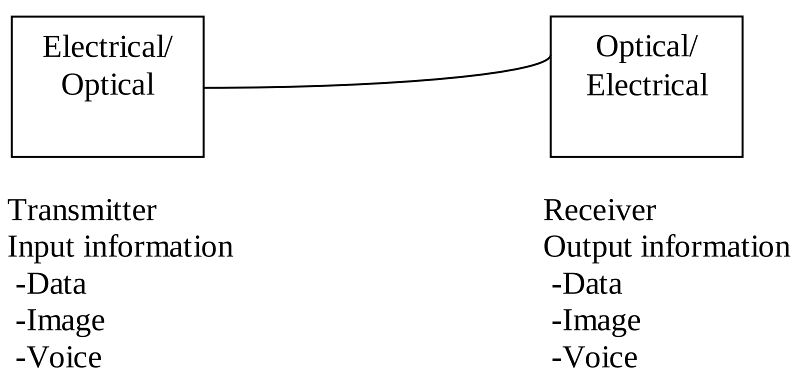


Figure 1.1 Basic optical fiber communication system.

1.2 Basic Optical Fiber System

The optical fiber system consisting of a transmitter section at the input terminal and a receiver at the output terminal. The transmitter section consisting of an optical source such as injection laser diode (ILD) or LED and a transducer, used to convert the input information (data, image, and voice) into an electrical signal, and then electrical to an optical signal, which is injected into the optical fiber by ILD or LED. This light signal is transmitted by using optical fiber to the receiver. The receiver section consisting of a photodiode such as a p-i-n photodiode, which is used to convert the light signal into an electrical signal and then in the user's desired form (data, image, and voice).

The transmission of the optical signal through the optical fiber is based on the phenomenon of total internal reflection. The phenomenon of total internal reflection was first demonstrated by John Tyndall in 1854 [4], which guided the light through the water stream. The optical fiber is used in various medical applications such as imaging, endoscopic surgery, etc. The laser was first developed by T.H. Hughes research laboratories in 1960 [5] [6]. This work is based on Arthur Leonard Schawlow and Charles Hard Towne's theory. The injection laser diode (ILD) was first invented by Robert N. Hall in 1962 [7]. Now, the ILD has used all types of laser printers, optical fiber communications, and disk players. Charles K. Kao, in 1966 studied experimentally and theoretically that the optical fiber can be used as a medium for long-distance communication and have high signal carrying capacity [8]. Initially, the optical fiber suffered from a high signal attenuation of about 1000dB/km. But after the invention low loss optical fiber has been developed (0.002dB/km).

1.2.1 Optical Network Generations

Due to the advancement in the manufacturing of optical fiber and the semiconductor industry, the high-speed optical network has been developed globally which is based on optical fiber. Figure 1.2 shows the first to the fifth generation of the optical network. The first generation of optical fiber is started in the early 1970 with the help of plesiochronous digital hierarchy, (PDH) for point-to-point optical fiber communication. Initially in first-generation communication is performed in the electrical domain by using time-division multiplexing (TDM) not in the optical domain.

But in second-generation PDH is replaced by multiplexing synchronous hierarchy. In this second-generation optical network, numbers of voice signals are transmitted over the optical channel by using an asynchronous hierarchy. This synchronous hierarchy is also known as synchronous optical networking (SONET) in Canada and the US, but in the rest of the countries, it is known as a synchronous digital hierarchy (SDH). For the handling of signal transmission, different protocols are introduced such as asynchronous transfer mode (ATM) and Ethernet. These protocols are used in a higher layer, not in the optical layer. The SONET /SDH cannot meet the requirement of higher bandwidth.

In third-generation optical networking, several new technologies have been developed and implemented. The number of the optical signal are multiplexed and transmitted by using a wavelength division multiplexing (WDM) technique on a single fiber. For long-distance communication, the stimulated emission is employed in an optical amplifier to amplify the light signal. The signals in the fiber suffered from dispersion, which can be reduced by using dispersion compensated fiber (DCF) and the optical regenerator can be avoided up to 1000km. In WDM various signals used the different wavelengths in the optical path. Optical cross-connects (OXC) and optical add-drop multiplexing (OADM) are performed by optical cross-connects and add-drop multiplexers in optical networking.

In the fourth generation, optical communication, dense wavelength division multiplexing (DWDM) are introduced. In DWDM the channel is tightly packed and able to use the bandwidth efficiently. The reconfigurable optical add-drop multiplexer (ROADM) is used to improve optical networking. In the early 1990 and 2000, the optical telecommunication network (OTN) [9] standard has been introduced. An OTN is used for operation, administration, maintenance, and provisioning (OAMP) in the optical layer. OTN defines the frame that is a digital wrapper to create a protocol optical data unit (ODU) similar to SONET/SDH. OTN is a very good transport network that provided transparent data mapping. The data transmission rate of DWDM is 40 and 100 Gbps. It cannot meet the next generation (5^{th}) higher bandwidth demand.

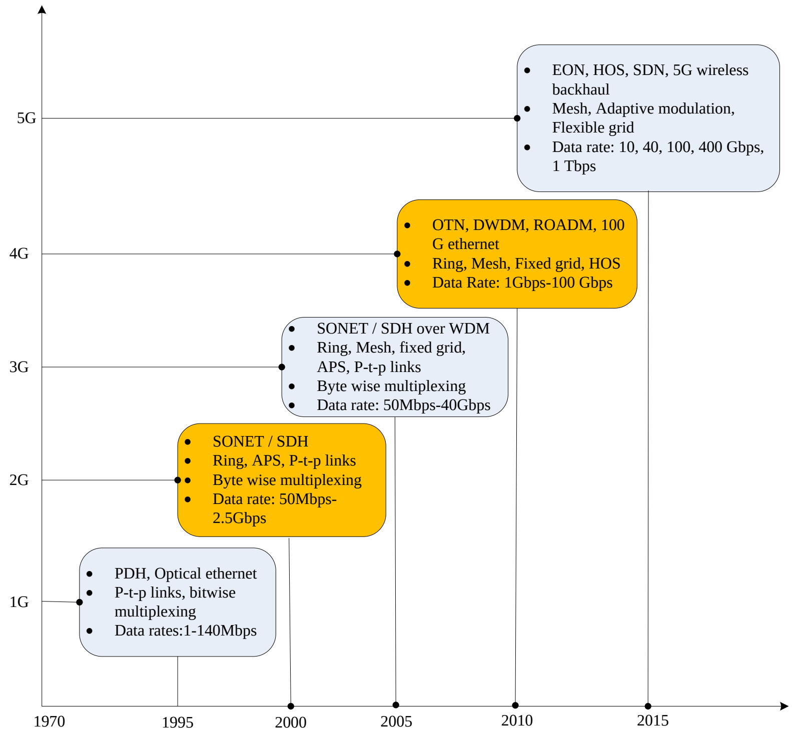


Figure 1.2 The generation of the optical network: Plesiochronous digital hierarchy (PDH), a synchronous optical network (SONET), Synchronous digital hierarchy (SDH), Elastic optical network (EON), Automatic protection switching (APS), Wavelength division multiplexing (WDM), Hybrid optical switching (HOS), Software-defined network (SDN), Optical transport network (OTN).

The next generation or fifth generations optical network requires more bandwidth to meet the higher bandwidth demand in the future worldwide. This can be done by using some latest optical components, which can provide a software-based optical controlled path and flexibility in bandwidth. The next-generation optical network used the elastic optical network (EON), which is also known as a flexible optical network (FON). The software-defined network (SDN) or EON is able to provide variable bandwidth as per the user demand and high-speed networks for various multimedia services such as video conferencing, online gaming and cloud application, etc. The EON can provide the bandwidth in multiples of 6.25 GHz, 12.50 GHz, and so on. The EON has a higher data rate of 100Gbps, 400Gbps, and up to 1Tbps.

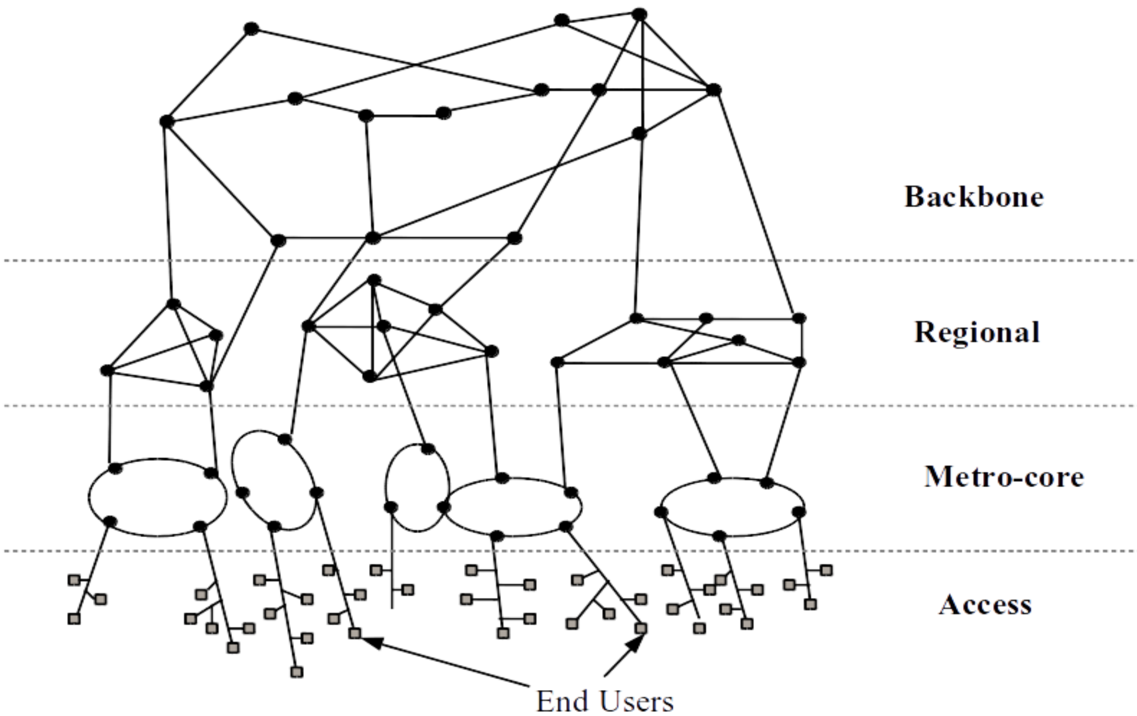


Figure 1.3 Geographical communication network architecture [10].

1.2.2 Communication Network Architecture

The communication network has been designed according to the user's requirement, which consisting of four segments that are backbone, regional, metro, and local access network as mentioned in figure 1.3. The whole network is based on the number of users, geographical range, and capacity requirement [10]. The local access network spans only up to a few kilometers which covering hundreds of users. The transmission rate of the local area network depends on the end user's requirement and the technology implemented. Metro network supports different types of multimedia applications such as leased lines, voice services, data storage, and peer-to-peer communication system, etc. It spans up to hundreds of kilometers. Metro network is able to provide bandwidth as per the user requirement by installing the latest equipment. The regional networks exchange information between multiple metro networks. The regional network spans hundreds to thousands of kilometers covering thousands of users simultaneously. The regional network is interconnected through the backbone network. The backbone network spread more than thousands of kilometers covering millions of users. Backbone provides very high speed ranging from Terabits per second (Tbps) to Peta bits per second (Pbps) by using DWDM technology and the latest one is EON. The backbone network consisting of the optical add-drop multiplexer (OADM), optical cross-connects (OXC), and optical switches.

Initially, the new technology is implemented in the backbone network which affects a larger network area and responsible for a large amount of traffic. After a few years, this technology is implemented differently in the lower network layer that is regional, metro, and local area networks. The local area network does not require higher bandwidth all the time it uses a passive optical network (PON) to connect the end-users.

1.3 Technology-Based Optical Network

The optical network is driven by different layers such as optical, IP, and SDH. There are sub-networks and PSTN. The service network is supported by ATM, OTN, and SDH. The client network services are carried by server network the relationship between the network layers is very important. The service network layers have more client layers. SDH is supported by an optical network and can have an ATM network and IP. For future communication, users need a high-speed network that can achieve by the software-defined network (SDN) and EON. The survivability of the optical network is the major challenge for future communication networks. The network layer can be controlled individually and able to create an end-to-end light path, the network operator sets the light path manually to each layer.

1.4 Objectives

Based on the literature review and research gaps, the main objectives of this research is to reduce the probability of failure in optical network or to provide faster connection recovery in case of a single and dual-link failure in EON. The sub-objectives of this whole work are as follows:

i) Design of halfway signal exchange-shared path protection (HSE-SPP) algorithm for a single link failure in EON.

ii) Proposed a path-based fast connection recovery scheme for single link failure.

iii) Proposed a link-based rapid recovery scheme for a single link failure in EON.

iv) Design an intermediate node cross-connect backup for shared path protection (INCB-SPP) for a dual-link failure in EON.

1.5 Structure of the Thesis

Chapter 1 Introduces optical communications. The brief introduction and importance of the optical network are presented in this chapter.

Chapter 2 Literature survey is presented in this chapter and various survivability scheme for a failure in the optical network has been discussed.

Chapter 3 In this chapter we described the DPP and SPP and formulated a halfway signal exchange-shared path protection for a single link failure in EON with a failure notification message to the source and destination node simultaneously.

Chapter 4 Here, in this chapter, we implemented a path-based recovery scheme for a single link failure in EON.

Chapter 5 Presented a link-based fast connection recovery scheme for a single link failure in EON.

Chapter 6 In this chapter a new fast connection recovery scheme has been proposed, which is an intermediate node cross-connect backup for shared path protection (INCB-SPP) for a dual-link failure in EON. The maximum survivability has been achieved by sharing other alternate backup routes in the network.

Chapter 7 Finally, this chapter provides the conclusion of the whole research work carried out in the thesis and the future scope of this work.

CHAPTER 2
LITERATURE SURVEY

2.1 Optical Networks Survivability

The detailed literature on the survivability of optical networks has been explained in this chapter. The migration of a fixed optical network to a flexible optical network/elastic optical network has been explained in [11]. As the number of internet users increases rapidly [12], the higher network speed and bandwidth demand are also increasing worldwide. The WDM-based optical network also provides high bandwidth, but cannot meet the future bandwidth demand. WDM-based fixed grid provides 40 GHz and 100 GHz channel bandwidth. To meet the higher bandwidth demand, the elastically optical network (EON) architecture is proposed. The spectrum sliced elastic optical path (SLICE) [13] network in the literature is called Elastic Optical Network (EON) or Flexible Optical Network (FON) which provides the variable bandwidth as per the end-users requirement, which is an integer multiple of 6.25 GHz, and 12.50 GHz and so on. The EON can support very high bandwidth demand that is 400 Gbps and 1Tbps. The EON has many advantages over the fixed grid such as more bandwidth, higher capacity, and efficient spectrum utilization.

The path and link-based protection/restoration schemes for different failures (link and node) in WDM optical networks have been presented in [14]. The link and node failure in the optical networks resulting the failure of several optical channels simultaneously which leads to huge data and revenue loss to the network operator. The wavelength capacity requirements for primary and backup route and routing assignment were also examined in [3]. The proposed approach provides the survivability for multiple failures in the network. The switching recovery time and restoration time have also been explained.

The shareable bandwidth reconstruction strategy in elastic optical networks has been proposed in [11]. The survivable ILP model has been proposed for EON. The proposed scheme can share the same capacity with multiple requests.

In ref. [15] analyzed the key features of survivability in optical networks. The recovery of the network is defined as the network which provides continuous services even after the failure happens in the network. The throughputs of the optical fiber network are in Gbps and Tbps.

Survivability is also important for conventional optical networks. The fast survivable sub path protection for WDM networks are explained in [16]. The large optical network is divided into the smaller domain and proposed subpath protection, and shared path protection (SPP). The routing and wavelength assignment problem is studied in [16].

The disaster survivability for optical communication is presented in [17]. The failure in the optical networks due to disasters such as earthquakes, fire, and landslides, etc. required different treatment. The different disaster requires different treatment. Every network has been designed or installed with some excess capacity, which provides protection (provisioned before the failure occurred) and restoration (provisioned after the failure) in the optical network.

The survivability for the submarine optical network is proposed in [18]. The survivable optical network has been designed for a submarine disaster such as nuclear explosion and earthquakes. The two nodes problem is examined by considering different two islands. The joint multidimensional resource algorithm for software-defined elastic optical networks has been proposed in [19]. The proposed bandwidth allocation algorithm is greatly improved as compared to other algorithms.

The intermediate (IR) and advance reservation (AR) scheme for EON has been studied in [20]. The quality of service (QoS) protection scheme [21] for flexible optical is proposed in [22]. The routing and spectrum assignment (RSA) for EON is presented in [23]. The average growth of internet traffic grows rapidly, which has been forecasted by Cisco from 2017-2022 [24], 2018-2023 [12], and the compound annual growth rate (CAGR) is addressed in [25].

The survivable strategy for WDM networks has been proposed in [26]. The quasi path restoration scheme for a failure in EON has been presented in [27]. The various network parameters for different topologies (COST239, NSFNET, and ARPANET) such as BBP, network fragmentations, NCU, bandwidth provisioning ratio, and resource utilization ratio has been simulated in MATLAB and compared the result with SPP.

The multi backup path strategy has been proposed in [28]. The backup spectrum reservation, with multipath protection (BSR-MPP) for survivable EON, is proposed. This scheme (BSR-MPP) minimizes the spectrum conflict problem between the primary backup paths. The survivable path-based protection strategy for a double link failure is explained in [29]. In [30] the recoverable traffic cognition algorithm for dual failure in the flexible optical network has been proposed. The traffic recoverability maximizing for double link failure is addressed in [31]. There are three different recovery models are proposed. In [32] the space division multiplexing (SDM) EON has been considered to provide flexibility and capacity in future transport communication networks. The RSA problem is also addressed.

The survivability mechanism of optical fiber for military transmission network are addressed in [33]. Different modes of protection are discussed in detail and compared with the link and channel-based protection schemes. The different survivability schemes are proposed.

2.2 Survivability schemes in elastic optical networks

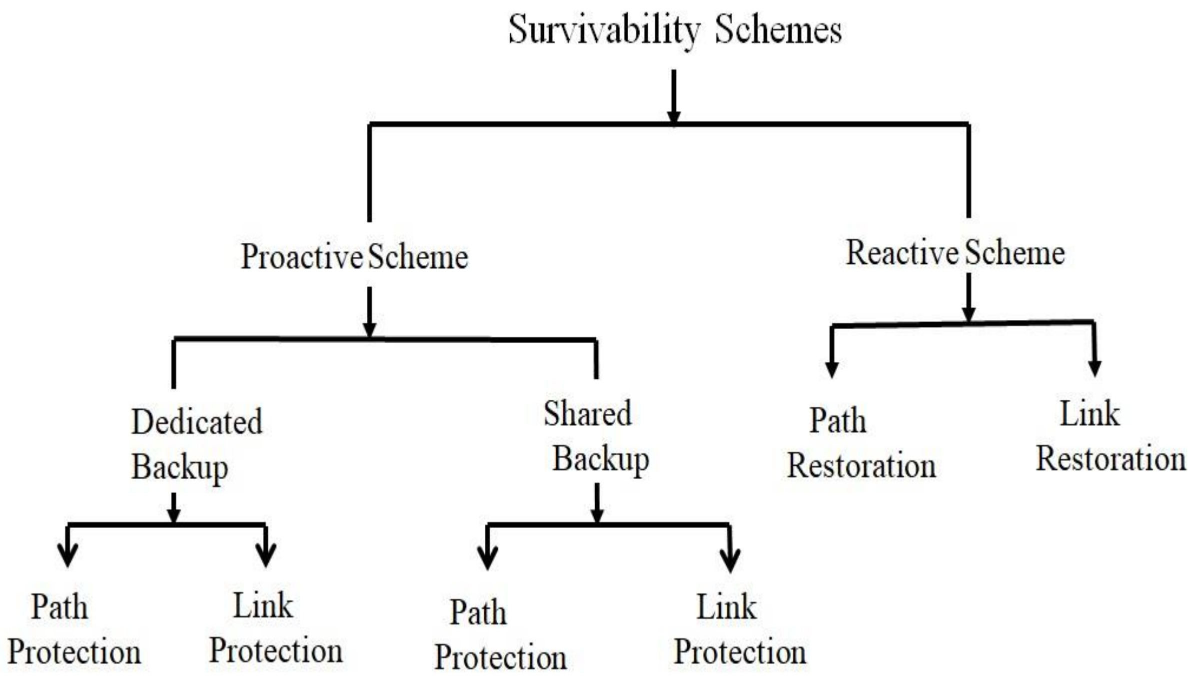


Figure 2.1 Different recovery schemes for a failure in the optical network [14].

There are various survivability schemes discussed in the literature [14]. Survivability generally refers to the network which provides continuous services even after the failure happens in the network. The protection schemes are classified into two categories. One is a proactive/ protection scheme and the other is a reactive/ dynamic restoration scheme as shown in figure 2.1.

2.2.1 Proactive scheme

In this scheme, the design of the recovery scheme for the optical network is pre-planned. In a proactive scheme, the backup resources (such as switches, fibers, available frequency slot, etc.) are reserved in advance at the time of connection setup or at the designing of the network. This scheme provides a hundred percent recovery guarantee and provides fast recovery, but the bandwidth gets wasted. The dedicated path protection (DPP) are of two types as shown in figure 2.2 (a) and (b), one is 1+1 DPP or automatic protection switching (APS), and the second is 1:1 DPP/APS, and 1:N shared path protection (SPP) as mentioned in figure 2.3 are the proactive schemes used for the recovery of a failure in the optical networks.

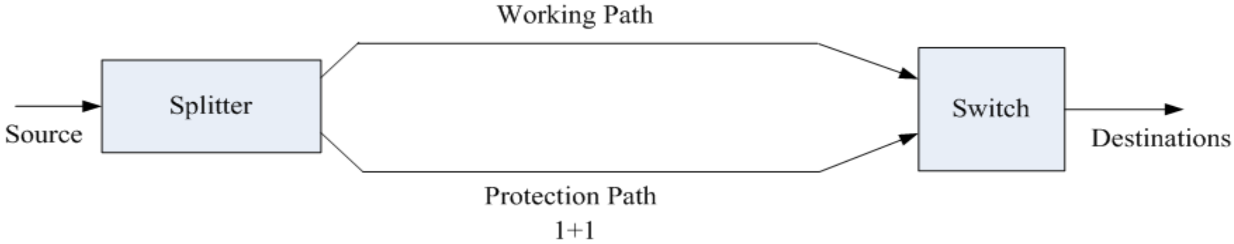
2.2.1.1 Dedicated path protection (DPP)

As 1+1 DPP scheme is shown in figure 2.2 (a), the traffic is sent over two parallel paths, that's on the working and protection path simultaneously, and the destination node compares both the signal and selects a better one [15] (e.g. less noisy). In case of failure, the destinations switch onto the protection path. This scheme is simple and fast, but bandwidth gets wasted.

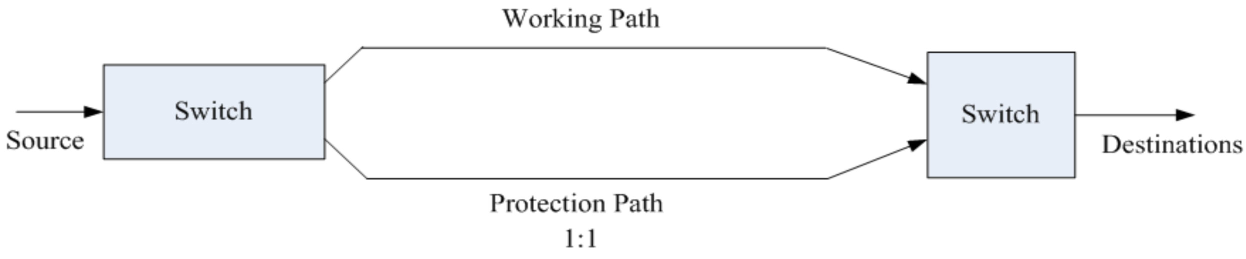
In 1:1 DPP as provided in figure 2.2 (b), during normal operation no traffic, or low priority traffic has been sent through the protection path. In case of failure in the network the source and destination node switch on to the protection path. This scheme has better resource utilization, but the recovery process is slower.

2.2.1.2 Shared path protection (SPP)

In *1:N* SPP there are *N* numbers of the working path which shares a single protection path. In case of failure happens in *N* numbers of the working path then a single protection path provides the recovery [15]. In *m:n* SPP, there are *n* numbers of working path, and *m* numbers of the protection path. If there more than *n* numbers of links that fail simultaneously, then the traffic is re-routed through pre-assigned priorities. In SPP the sharing of the backup resources reduces the cost of backup resources as compared to DPP.



(a)



(b)

Figure 2.2 (a) 1+1 Dedicated path protection (DPP) (b) 1:1 Dedicated path protection (DPP) [14].

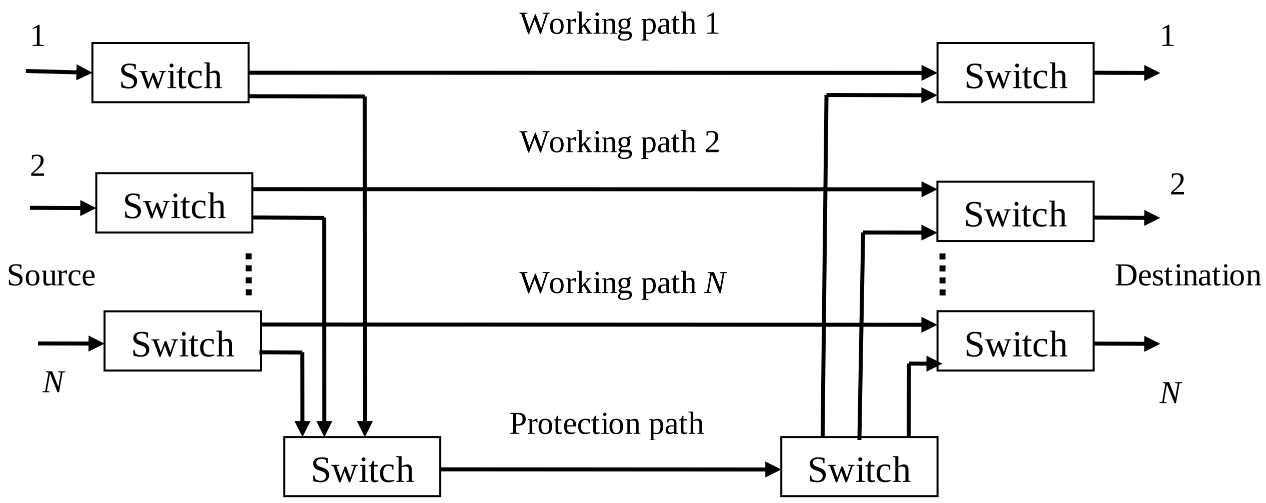


Figure 2.3 1:N Shared path protections (SPP) [14].

There is also two type's protection as shown in figure 2.1 that's path protection and link protection.

2.2.2.1 Path protection

The path protection is mentioned in Figures 2.2 (a) and (b), and in Figures 2.3 and figure 2.4 (a), in this scheme the failure is handled by source and destination node [34]. This scheme is more efficient but the recovery time is more. If the failure occurred on the primary path between nodes 2-4 then the adjacent node (node 2) to the failure sent the failure notification message to the source node. The source node switches the whole traffic onto the backup route through 1-3-5-6. If there's no route (FS) available for the backup path then the connection request gets rejected.

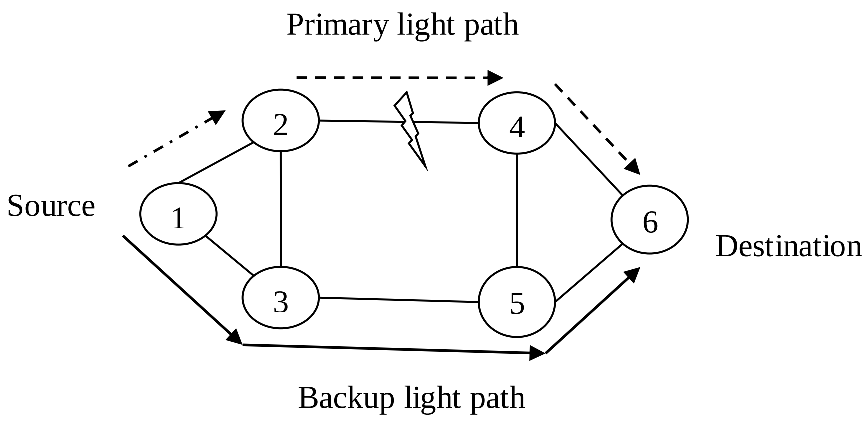


Figure 2.4 Path protection scheme [34].

2.2.2.2 Link protection

In link protection, the failure is handled by the adjacent nodes to failure as shown in figure 2.5 [14]. Here, the primary route is used for whole traffic, if the failure occurred on this route between nodes 2-4, then this failure is handled by the adjacent node to failure that's node 2 and provides a protection path through 2-3-5-4. This scheme is less efficient, but the recovery time is faster than path protection.

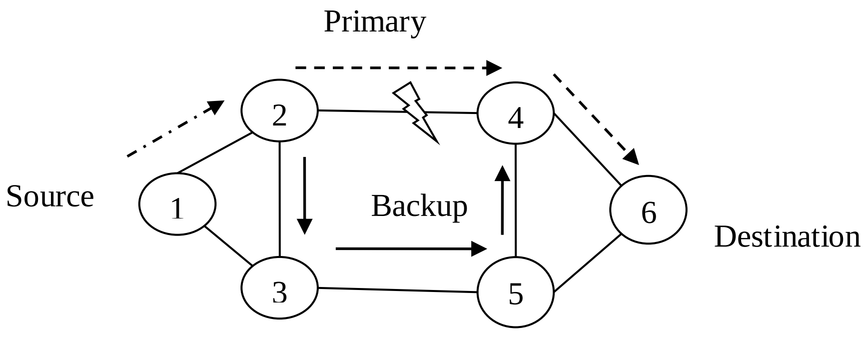


Figure 2.5 Link protection scheme [14].

2.3 Reactive scheme

In this scheme, the backup resources are not reserved at the time of connection establishment, but dynamically searched some spare capacity from the fiber, available FS, and switches after the failure happens in the network. This scheme can't guarantee the recovery of any failure in the network and it requires a longer time for restoration. But it's more efficient in terms of resource utilization. Its' also classified into path and link restoration.

2.3.1 Path restoration

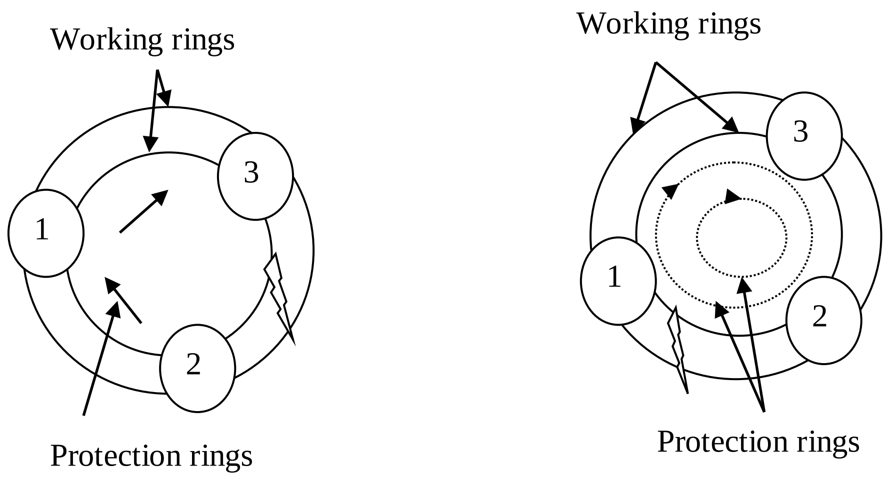
In path restoration, the failure is handled by the source and destination node simultaneously as shown in figure 2.4. in this scheme, the backup route is searched dynamically after the failure I the network as shown in figure 2.4. If no FS is available then the connection request gets rejected.

2.3.2 Link restoration

The failure is handled by the adjacent node to failure as shown in figure 2.5. This scheme provides a faster recovery. There is also a dedicated link protection/restoration (DLP) and shared link protection/restoration (SLP). Some backup FS are reserved at the time of connection setup, but in link restoration, it's not possible to provide a backup link to every primary link. It has been observed that the DLP utilizes the bandwidth inefficiently [14]. In SLP backup link is shared with other backup links (sharing of resources) and it's more capacity efficient than DLP.

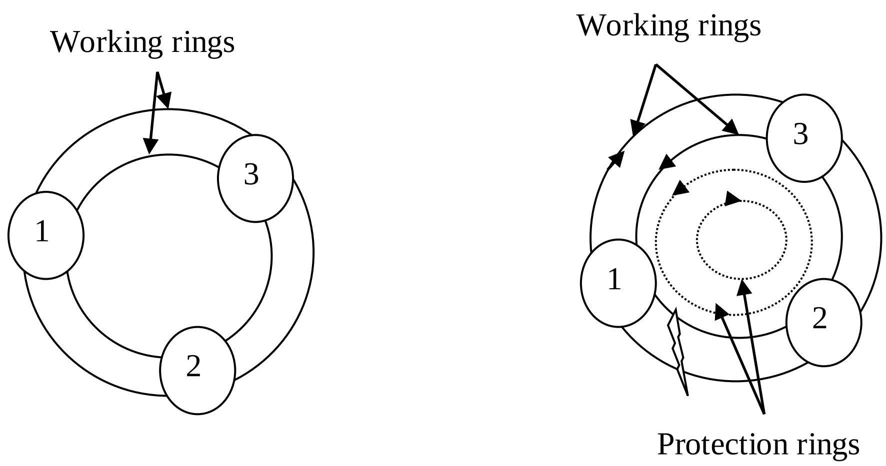
2.4 Self-healing ring (SHR)

The shelf healing ring is also a very successful recovery technique in optical networks [35]. In this scheme, the ring architecture is designed for working and protection paths. The SHR technique is more flexible than DPP and SPP as it is able to handle both node and link failure simultaneously. The use of a high-speed add-drop multiplexer makes it more convenient and attractive for survivable optical networks. The SHR is also of two types one is a unidirectional self-healing ring (USHR) as provided in figure 2.6 and the other is a bidirectional self-healing ring (BSHR) as shown in figure 2.7.



(a) (b)

Figure 2.6 Unidirectional self-healing ring (USHR) (a) working rings and (b) protection rings [35].



(a) (b)

Figure 2.7 Bidirectional self-healing ring (BSHR) (a) working rings and (b) protection rings.

The traffic flow is different in USHR and BSHR during normal operation. In USHR the traffic flow is only in one direction as shown in figure 2.6. The traffic flow through the protecting path, only when the failure occurred on the opposite side. In USHR the traffic is protected by line and path protection. If the failure occurred between node 2 & node 3 as in figure 2.6 (a) then the protection is provided by line through node 2-1-3. In figure 2.6 (b) the two parallel working paths and the same as the 1+1 DPP scheme. In BSHR the traffic flow is in both the direction as shown in figure 2.7 (a) and (b), if any cut occurred between nodes 1-2 the protecting backup route is provided, which is reserved in advance at the time of connection setup. Here, the two working fibers have also two protecting fibers. Hence, the capacity of the fiber is fully utilized.

2.5 Automatic double-cycle covers (ADCC)

An automatic double-cycle cover (ADCC) to protect the optical network was first introduced by G. Ellinas *et al.* in [36]. The ADCC is implemented for mesh network and every primary route have one protecting fibers. Every link has four unidirectional links and every two links are used to transfer the data and the other two are used for the protection in the opposite direction of the working link. The backup route is used as a set of cycles for every protection link that occurs merely once in any provided cycle as shown in figure 2.8.

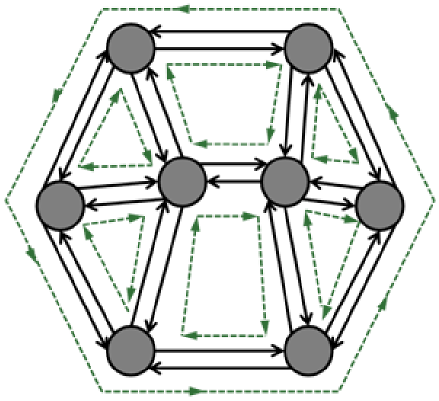


Figure 2.8 Implementation of Automatic double-cycle cover (ADCC) [36].

2.6 Loopback scheme

The loopback scheme is implemented in [37]. The whole network is divided into sub-graphs (that's in primary and secondary). The primary sub-graph is used to transfer the data and the secondary is used for a backup link. Here, we consider that every link has two fibers in a different direction. Hence the subgraph is formed by choosing one fiber for primary and the other for secondary from every route. If the failure happened then the primary route is looped back with the same FS on the secondary. The signal reaches at another end of the failed link and switch automatically to the primary sub-graph as shown in Figures 2.9 (a) & (b). The dashed line indicates the primary and dashed and the dot indicates the secondary subgraph.

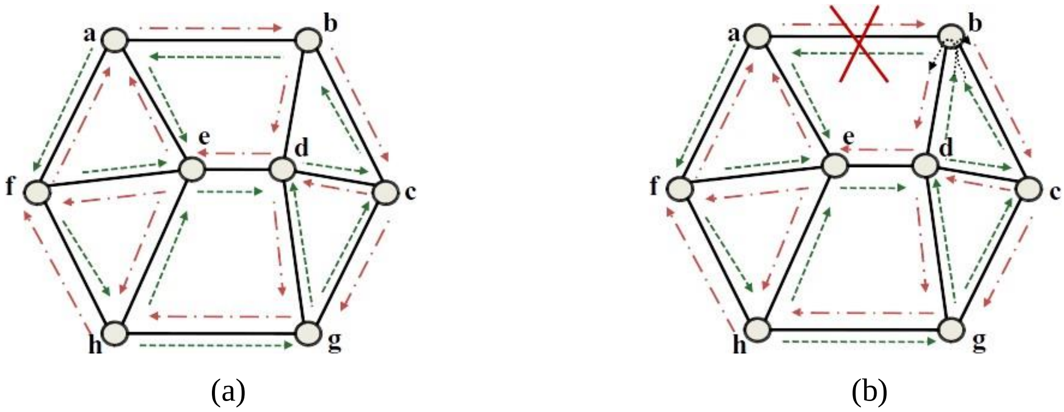


Figure 2.9 (a) Primary sub graph loop back, and (b) Secondary (dashed and dotted lines) sub-graph with protection fibers [37].

The working route on the primary subgraph from node *b-a* via node *ab* and gets loopback at node *b* on the secondary graph. The traffic of the backup route finds its path at node *a*. the backup route can take different possible numbers of the path to reach the destination *a* as shown in figure 2.9 (b). The route on which the data is initially transmitted is chosen as a backup light path and later path gets rejected. In this only one backup route is considered.

2.7 P-Cycle protection scheme

P-cycle protection schemes or preconfigured protection schemes were first proposed by Grover *et al*. in [38]. The researchers found more interest to implement this scheme due to its fast recovery and efficient utilization of the resources. The p-cycle provides the backup route to the primary link as well as to the spanning links. When the spanning route fails, a p-cycle has two routes to re-route the traffic through the spare capacity. Hence, the requirement of capacity in this scheme is reduced to half in the spanning link. In figure 2.10 (a) the p-cycle is shown by dotted lines and there is no link fails. If the failure occurred on any link, then the recovery has been done by re-routing the traffic on the p-cycle by switching to the end nodes of the failed route. The spanning route has two protection links as shown in figure 2.10 (c). The protection on the p-cycle and on the spanning link is provided in figures 2.10 (b) and (c) respectively. P-cycles are used to protect the links, nodes, and paths in optical communication. The producing and terminated data can't be protected by re-routing the traffic. When any node fails, then only the transiting data flow can be protected. The encircling of the p-cycle is used to protect the failure link.

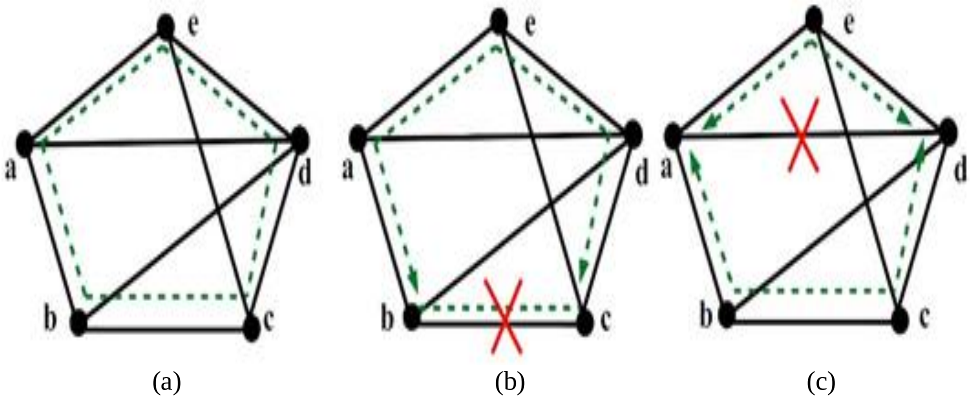


Figure 2.10 P-cycle protection schemes [38].

The node encircling p-cycle (NEPC) scheme and failure independent path protecting (FIPP) p-cycle has been proposed in figure 2.11 (a) and (b) respectively. In figure 2.11 (a) the dotted lines of NEPC and dash dots which indicating the protection of transiting flow through node *a*. The protection of links by using p-cycle is extended to path-based protection that's FIPP as mentioned in figure 2.11 (b). Here, the FIPP p-cycle is shown in green dots which protecting the disjoint paths, and the protected disjoint path is shown by dot-dash lines.

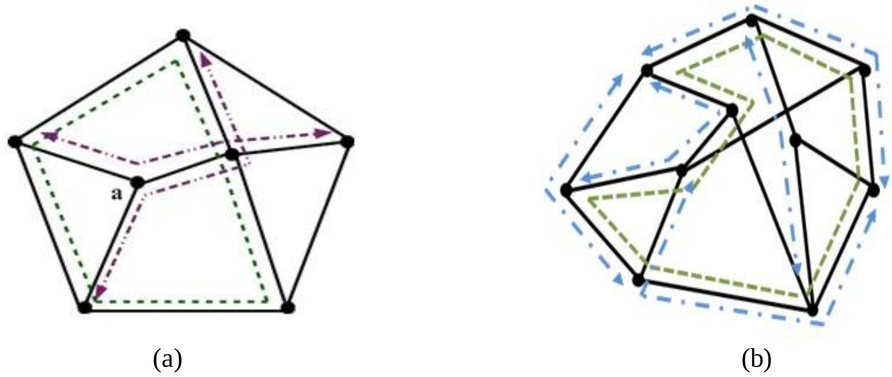


Figure 2.11 Protection using (a) Node encircling p-cycle, and (b) Failure independent path protecting p-cycle [39].

The protection of the link can be provided through an end-to-end node or using path segments or traffic flow recovery p-cycles. The flow recovery p-cycle and path protection segment are more efficient as compared to link protection p-cycles. The protection by flow p-cycle is difficult to implement to the whole network and it's a slow recovery process. The p-cycle finding with minimum use of resources is the critical optimization problem in the survivability of the optical networks. The p-cycle scheme is broadly described in centralized and distributed strategy. In a centralized strategy, the p-cycles are chosen from the set of cycles by fulfilling the network graph criteria. The ILP is the centralized optimization strategy for the optical network. ILP includes share capacity optimization, spare capacity optimization, and working path-protected capacity optimization. Spare capacity optimization involves the primary and p-cycle routes jointly. This scheme is more complex and required a longer time for operation. While the spare capacity optimization involves the pre-computed p-cycles to protect the primary route in the network. The working path-protected capacity optimization is used to protect all the working channels. The ILP based optimization problem has been considered for dynamic and static data transfer. The formulation of ILP is more complex as more numbers of variables are used and the ILP solution falls into NP problems. ILP optimization provides a fast result for smaller networks and also useful for the recovery of the larger optical network. A network of up to 100 nodes can be optimized by ILP to provide an optimal solution. For designing p-cycles the heuristic algorithm is also used. Heuristic algorithm required very little time than ILP. But the ILP is more efficient than heuristic algorithms.

The p-cycle based survivability scheme has been explained in [39] for WDM networks. The p-cycle recovery scheme has been considered a very good approach for survivable optical networks. This p-cycle recovery scheme has also an important impact on dual-link failure in the optical network. The fast recovery time and efficient utilization of the network capacity can be achieved by using the p-cycle in optical networks. The protection in the elastic optical network by using p-cycle failure independent routes is provided in [40]. It provides the complete survivability for a single link/ double link failure. The use of Hamiltonian cycles with p-cycles reduces the length of the backup route [41].

2.8 Survivability for multiple failures in optical networks

The multipath survivability scheme with energy efficiency for EON has been proposed in [42]. The two-step ILP is proposed for minimizing energy consumption by the network element for small networks. The efficient dynamic routing and spectrum assignment for multi-fiber EON is provided in [43]. The path selection probability is calculated by using the ILP model. The repair of the failed link required much more time that may be in hours, but the recovery of the data by using a pre-assigned backup route is fast. At the same time, another failure may also occur in the network. Or multiple failure occurred in the network at the same time due to some disaster like weapons of mass destruction (WMD) earthquake, landslide, cloud burst, and cyclone etc., these are called correlated failure in the network. Sometime, uncorrelated failure often occurred in the network, like a set of link fails simultaneously in the network due to weather disturbance etc. (such as heavy Rain). The natural disaster caused huge data loss and revenue loss to the network operator as well as to the government. For example, the Sichuan earthquake in 2008, in which 30,000km optical fiber cable and 4000 base station have been damaged [44]. Also, Hurricane Katrina happened in 2005 cut 99.99% of optical network connectivity to the rest of the world [45]. Similarly, the Japan earthquake on April 07, 2011, also damages several telecommunication networks (e.g. telephone poles, optical fiber cables, telecommunication offices, and buildings) [46] which takes several days to recover from the failure. In the present scenario, all the business and social activities depend on the optical fiber network. The failures due to disaster are categorized as deterministic and probabilistic models. In the deterministic approach, the probability of the disaster is equal in some specific regions, whereas the probabilistic approach considers only the intensity of the failure [47]. There are different recovery scheme for multiple failures in the network has been provided in the literature. The multipath routing has been implemented in several papers [48]. In the case of multipath, the whole traffic is partitioned and sent on multiple disjoint routes to increase the transmission speed of the whole network. Several reactive schemes have been provided in the literature for combating multiple failures such as re-optimization and re-provisioning in the network capacity. The multipath routing scheme is also provided in [21].

2.9 Survivability for a dual-link failure

The recovery of a dual-link failure required more resources and the design of a survivable scheme is more complex for dual-link failures as compared to a single link failure. There are different protection schemes such as DPP, and SPP, path, and link protection as described in the earlier section. A double link failure recovery model for optical mesh networks is proposed in [49]. A heuristic algorithm has been developed, which provides a 100% pre-computed backup path to the double link failure. The DPP and SPP can also be extended for the recovery of dual-link failure. The survivability for dual-link failure by using p-cycles is implemented in [50] [39]. The p-cycle based recovery schemes for a dual-link failure provide a quality service in the optical network. The tie-based fault tolerance strategy (TBFT) is also very useful for the recovery of dual-link failure [51]. In this scheme, all the edges of the network are covered by using distributed control method. The predesigned *k*-edge protection scheme for multiple failures is implemented in [52]. In this scheme, the whole topology is divided into subgraphs and these subgraphs have *k*-link disjoint backup routes between the nodes.

CHAPTER 3

PROACTIVE RECOVERY SCHEME WITH TIME CONSTRAINT FOR ELASTIC OPTICAL NETWORKS

In the last few years, the number of internet users increases rapidly worldwide. The use of internet changes the society working lifestyle. Every internet user access different multimedia services such as online gaming, video conferencing, 5G, 3D imaging, and different cloud applications. The optical path is connected by different links between the different nodes. In this chapter, we present a halfway signaling exchange shared path protection (HSE-SPP) for the recovery of a failure in an elastic optical network. In the proposed HSE-SPP scheme, the intermediate node is chosen for the exchange of signals on the backup route. When any link fails in the network, the source and destination nodes generate a backup route to set up messages to the pre-assigned intermediate node on the reserved backup route. At the intermediate node, the process of signaling exchange occurs, and acknowledgment is generated and sends to the respective end nodes. Consequently, connection recovery time by applying HSE-SPP becomes very low. Simulations are performed for network parameters such as recovery time (RT), bandwidth blocking probability (BBP), bandwidth provisioning ratio (BPR) and resources overbuild ratio and are verified with existing strategies.

3.1 Introduction

In the last few years due to the huge technological revolution, the number of internet users increases which results in the accumulation of internet traffic proportionally. The use of the internet drastically changes the lifestyle of society; most of internet users access different multimedia services such as video conferencing, online games, marketing, 3D imaging, 5G, and cloud applications. These services demand a very high data rate. In order to meet such a high data rate, the optical network is the first choice of the service provider due to huge bandwidth availability. To accomplish future internet user's demand, transmission technologies require a more flexible and efficient utilization of network resources.

In a traditional optical network, the spectrum is subdivided into fixed wavelength slots of 50GHz or 100GHz by using a wavelength division multiplexer (WDM) [53]. The entire spectrum is divided into the integer multiple of the wavelength. Therefore, at least a minimum 40 Gbps/100Gbps data rate is assigned even lower data rate demand by the user. Consequently, the data rate is unused, and bandwidth cannot be utilized efficiently by service providers. Hence the spectrum wastage occurred in a fixed grid and cannot support sub-channel transmission [54]. Similarly, It has been seen that the fixed grid (usually at 50 or 100 GHz) is infeasible to transfer data rates over 100Gbps, 200Gbps, and 400Gbps, and also 1Tbps [55].

In order to meet these challenges, the elastically optical network architecture is proposed. The spectrum sliced elastic optical path (SLICE) network in the literature is called Flexible Optical Network (FON), or Elastic Optical Network (EON) which provides the bandwidth according to the requirement of the users or based on the services [56]. The elastic optical network can support multiple 6.25GHz bandwidth channels and able to carry variable data rates. The architecture of EON is flexible and based on the Tunable Bandwidth Variable Transponder (TBVT). The variable transponder can generate the signals according to the user's demand and to the distance of transmission. In EON some parameters like modulation format, wavelength spacing between the channels, and the data rate are flexible. The elastic optical network can provide a Quality of Services (QoS) and is a complete solution for the next generation of internet demand. The EON is a suitable replacement to the conventional WDM optical networks.

The elastic optical network EON [55], [57], [58] has seen promising applicants for the future high-speed internet demand. The EON has the ability to allocate the frequency slot (FS) according to the user's requirement. The EON can allocate the finer frequency slot such as 6.25, 12.5 or can be 25 GHz than that of 50 or 100GHz fixed grid WDM system, the BVTs used in EON able to provide the bandwidth from 10-200Gbps [59]. The bandwidth (BW) requested by the users is the multiple of these fine granular frequency slots. The utilization of the optical network capacity in EON is highly improved as compared to the WDM network.

The optical network establishment of the light path is based on the RSA strategy.

The route between the two nodes is assigned by a static or dynamic routing strategy. And for spectrum assignment, generally, first fit or random assignment is used. Spectrum assignment depends on the modulation format used for transmission. The selection of modulation formats depends on the route distance. Higher modulation formats are spectrum efficient but signal transmission distance is shorter. In addition to modulation format, spectrum assignment must fulfill the two spectrum assignment constraints, that is, spectrum continuity, and contiguity constraints. The continuity constraint, needs the presence of the identical number of FSs for every link in the optical route, whereas the spectrum contiguity constraint requires successive FS [58], [59]. The spectrum constraint brings additional complexity for designing the survivable EON as compared to WDM architecture.

In this chapter, a network survivability issue is addressed. When the failure occurred in the optical network leads to a huge amount of revenue and data losses. The failure in the optical network may be a link failure due to fiber cut, node failure, and damaging of the whole optical network due to some disasters such as earthquakes, landslides, and weapons of mass destruction (WMD) attacks. Therefore, designing the survivable optical network for a next-generation elastic optical network is a very important issue. The survivability in the network is the ability of the optical network to send the traffic of the failed link to the alternate route. The different recovery schemes have been discussed in the literature for the survivability of the optical network.

Survivability is mainly classified into two types: protection and restoration. In the protection scheme, the backup resources are predefined at the time of connection establishment which assures fast and 100% recovery after the failure of the primary route. There are several protection schemes, dedicated protection (DP/1+1) scheme in which 50% of the traffic split between the primary and backup routes. 1:1 is also the dedicated protection scheme in which only the primary route is used for the normal mode of operation, while no traffic or low priority traffic is sent through the protection route if the failure happened in the network, then source and destination switch onto the protection path. N: M where N is the primary route that carries the whole traffic if it fails then there will be an M number of backup routes are available.

In order to minimize the redundancy of the backup spectrum, a single link failure model is proposed. In a single link failure model, it is assumed at a time in the network only one link will be failed. At this time, the spectrum can be shared by protection path, if their respective primary routes do not fail concurrently. This process is known as backup multiplexing. In the restoration scheme, the backup path is searched after the failure occurred, it may not be guaranteed the backup route available for failed primary route.

The major contribution of the proposed work, to provide fast connection recovery and minimum resource utilization. In this paper, we proposed the halfway signaling exchange shared path protection (HSE-SPP) strategy for fast connection recovery and compared the results with existing SPP and DPP.

3.2 Related Work

There are various schemes that have been designed on the recoverability of the optical network in the literature. The survivability of the optical network is the major issue in future communication. During the failure of the communication network, the survivable networks have the capability to re-route the affected traffic through the safer link. There are two types of survivability schemes, first one is the protection scheme, in which the backup resources for the recovery of the failure in the network are reserved in advance, at the time of network establishment. And the second one is the restoration scheme, in which the backup route is dynamically searched only after the failure occurred. In some papers [60], [61] the comparison between the dedicated path protection (DPP), and shared path protection by using ILP and Mixed Integer Linear Programming (MILP) has been discussed and proposed a backup strategy.

In the literature various design of the networks are discussed for providing the QoS, proficient resource utilization and minimum bandwidth blocking probability (BBP) all are based on the management of the spectrum [60], [62]–[66], multipath protection [28], [67]–[69], p-cycle design [41], [70], [71], restoration [67], multicasting survivability [72], virtual network design [73], [74], and multilink failure [75], [76]. In paper [63], [77] first fit and last fit for primary, backup route and spectrum sharing have been discussed. The comparison between shared backup path protection (SBPP) dedicated path protection (DPP) is mentioned in [11], [59] which exposes that the SBPP occupies minimum space for backup path assignment.

In [61] some heuristic for shared path protection (SPP) has been proposed. The higher resource sharing and newest spectrum fragmentation by the backup route are discussed in [11]. The comparison for spectrum assignment and static routing with dedicated path protection (DPP) for different schemes are i) first fit, ii) supplementary graph-based routing and spectrum assignment (RSA), iii) the number of requested slices and the routing path length. The minimum-free-spectrum-block-consumption has been discussed in [78]. The re-scaled failure probability aware algorithm with ILP has been discussed in [62]. The available aware differentiated protection (ADP) algorithm is presented in [64] discussed the service level agreement between the users and the service providers. The performance of ADP, DPP, and SPP has been evaluated and compared, the comparison reveals that the performance of ADP is better than DPP and SPP. The shared path protection (SPP) with multiple failures has been discussed in [65]. The survivability quality for the flexible and permanent grid on the use of power and band utilization is presented in [79]. The Tabu search (TS) algorithm for SBPP and DPP has been discussed in [80]. The repair after failure optimization scheme has been proposed in [75]. In [74] the dynamic load balancing scheme has been presented for the survivability of the multilink failure. Hybrid single and multipath routing (HSMR) are discussed in [68]. The multipath routing and spectrum allocation (MRSA) for the multipath backup route are discussed in [66]. In peak hours the traffic is more and the probability of blocking the traffic is increasing in these pick hours [81]. The advantages of protection and restoration schemes for multipath survivability are discussed in [82] and bandwidth clutching for elastic optical networks is provided in [83]. The multipath protection (MPP) scheme for providing 100% survivability with path difference constraints is discussed in [84]. The Single Path Provisioning Multi-Path Recovery (SPPMPR) is presented in [67]. The multipath protection with the latest backup resource allocation is discussed in [28]. The preconfigured guaranteed available services and p-cycle design for the backup spectrum are presented in [41], [69]. The heuristic algorithms for dynamic and static traffic are provided in [20]. The optimization of multicasting and optimization of the light path which is 2 layer optimization schemes presented in [85]. The Virtual Optical Network (VON) based on the ILP for the survivable elastic optical network is discussed in [72], [73]. The Optimal Shared Protection Mapping (OSPM) scheme has been presented in [86]. The routing and spectrum assignment problem for multifiber EON has been provided in [43].

3.3 Proposed and Existing Strategies

This section explained the existing and proposed strategies. Furthermore, a detailed example of connection recovery is also presented.

3.3.1 Shared path protection (SPP)

In this scheme, the working and protection route is established during the connection setup. Backup routes shared the frequency slots of the network links, if their primary routes are link disjoint. The process of sharing of FSs over the network link is known as backup multiplexing. By using backup multiplexing, the assignment of redundancy backup resources decreases. However, due to backup multiplexing, cross-connection at the intermediate nodes increases the connection recovery time [27], [62].

3.3.2 Dedicated path protection (DPP)

In DPP, backup and working routes are allocated during the connection set up in a similar manner as in SPP. In the DPP, backup routes do not share the frequency slots. Therefore, a backup multiplexing mechanism does not occur and results in higher network resource assignment for the backup routes. But at the intermediate nodes, no need of cross-connection for the backup route. Thus, recovery time is lower than the SPP [27], [62].

3.3.3 Halfway signaling exchange shared path protection (HSE-SPP)

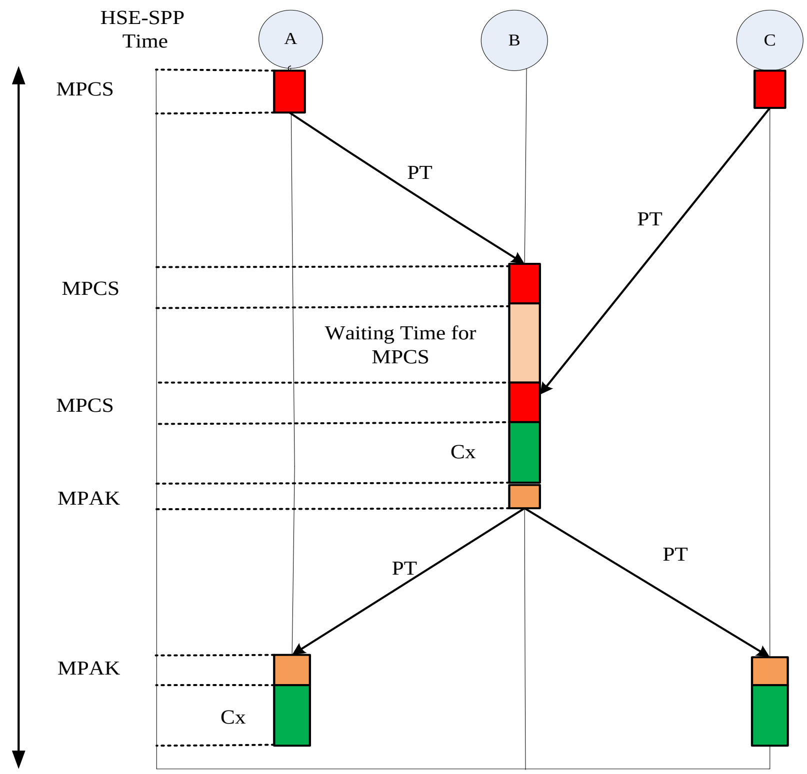
In HSE-SPP, on the reserved backup route, an intermediate node is chosen for the reception of connection setup messages sent by source and destination pair after failure. When the intermediate node receives connection setup messages from both the end nodes; it generates acknowledgment to the source and destination nodes for further communication. In Section 3.4, SPP, DPP, and HSE-SPP are explained in detail with an example.

3.4 Example of connection recovery in SPP, DPP, and HSE-SPP

Let us consider a connection request between source node A to destination node B. The primary route is A-B, and the backup route is A-B-C. At the time of connection failure, source and destination nodes detect the failure by failure notification messages. After the reception of the failure notification message, the connection recovery process initiates. In the connection recovery process, the source generates connection establishment requests via backup route and waits for an acknowledgment. The process of requisition of data transmission on the backup route is known as a two-way Signaling mechanism.

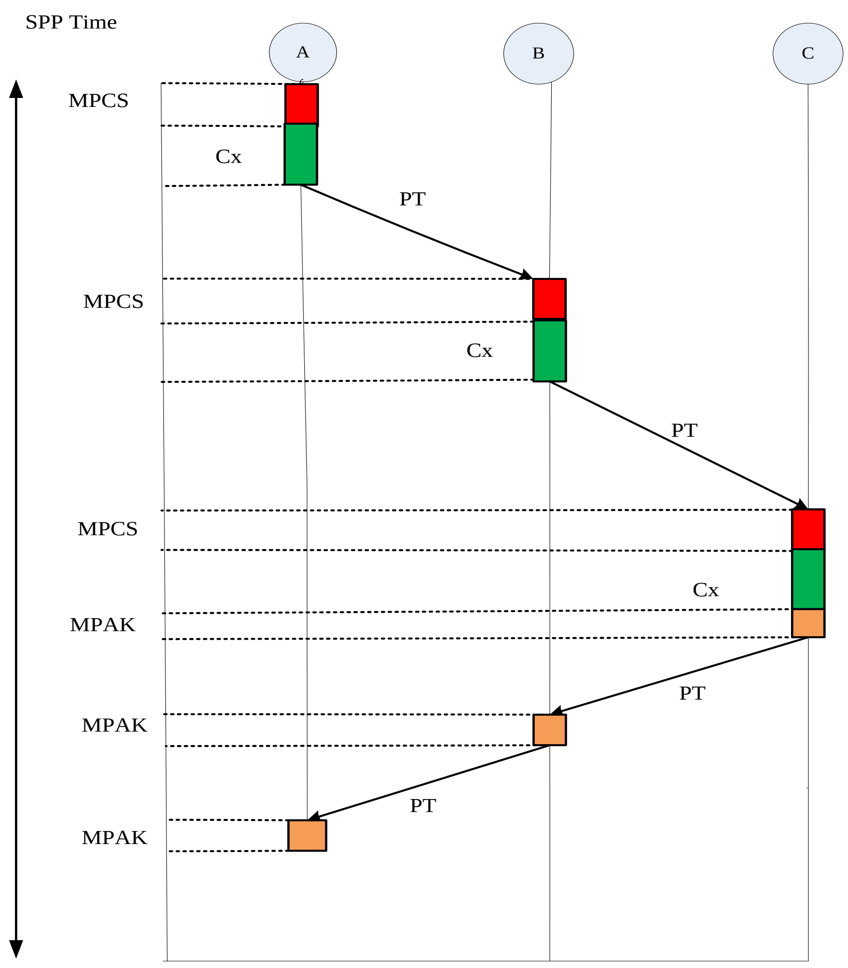
3.4.1 Shared path protection (SPP) connection recovery process

Figure 3.1 (b) shows the connection establishment time in SPP strategy is given. Source node A generates connection setup message MPCS i.e. message processing for connection setup, and also cross-connect switch (i.e. Cx) for the backup route. And, the connection setup message is transmitted to node B. Node B receives connection setup messages after propagation time (PT). PT is the propagation time of the message to travel from node A to B. Propagation time depends on the distance between the nodes. Node B repeats the same process of node A and forwards to the next node on the route. Node C is the next and destination of the messages. Node C also takes the same time for message reading and cross-connection as at nodes A and B. After reading the connection setup message, Node C generates acknowledgment to the source node A via backup route. The message processing (MPCS/MPAK) and propagation times of the acknowledgment message are the same as in connection setup messages. Note that, acknowledgment does not take cross-connect time.



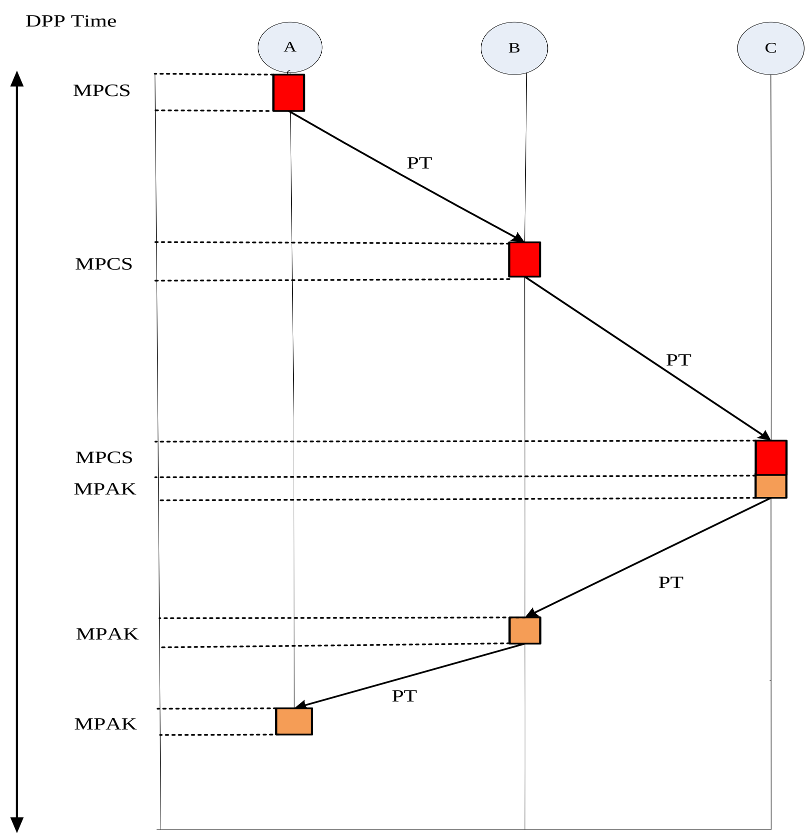
(a)

HSE-SPP Halfway signaling exchange shared path protection



(b)

SPP- Shared path protection



(c)

DPP-Dedicated path protection

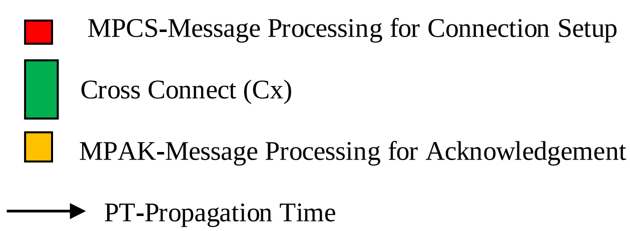


Figure 3.1 (a) Halfway signaling exchange shared path protection (HSE-SPP) (b) Shared path protection, and (c) Dedicated path protection (DPP).

In equation 3.1, the connection recovery time (RT) of SPP strategy for n number of nodes and ℓ length of the backup route is given. The parameter's value is given in Table 3.1.

Table 3.1 The average value of network parameters for various Survivable Strategies.

Network Parameters	**ARPANET**			**COST239**		
	DPP	SPP	HSE-SPP	DPP	SPP	HSE-SPP
Recovery Time (ms)	13.20	22.19	13.54	4.23	11.81	8.33
BBP	0.5626	0.2216	0.1870	0.4786	0.0873	0.0464
BPR	6.3072	3.2316	3.0255	3.5090	1.6697	1.6453
RO	3.7520	0.7028	0.5596	2.0418	0.2799	0.2633

$$RTSPP=D_f+2\times n\times(MPCS+MPAK)+n\times Cx+2\times \ell\times PT \qquad (3.1)$$

3.4.2 Dedicated path protection (DPP) connection recovery process

In DPP strategy, sharing of backup resources is not allowed therefore switches in the nodes of the backup route are already cross-connected. As a result, for connection recovery, time consumption in the cross-connection of switches does not consider. Figure 3.1 (c) shows the connection recovery process in DPP strategy. It is shown in the figure that cross-connection time for sending connection setup messages does not consider. Equation 2 is the connection recovery process for n nodes and ℓ length backup route.

$$RTDPP= D_f+2\times n\times(MPCS+MPAK)+2\times \ell\times PT \qquad (3.2)$$

3.4.3 Halfway signaling exchange shared path protection (HSE-SPP) connection recovery process

In Figure 3.1 (a) HSE-SPP is shown. In this process, firstly; a halfway node on the backup is chosen as an intermediate node where the Signaling exchange will be done. For the backup route A-B-C, Node B is assigned as the backup route as shown in Figure 3.1 (a). In HSE-SPP both the source and destination nodes generate connection establishment messages simultaneously after the occurrence of failure. In HSE-SPP, network resources are shared by backup routes, therefore, cross-connect time at the nodes is considered. After the reception of connection establishment messages from both the end nodes, Node B generates acknowledgment of the source and destination nodes. After the reception of acknowledgment, the connection establishment process is completed.

Let us consider ns-i/nd-i nodes on the backup routes between source/destination and intermediate nodes, ℓ s-i / $\ell_{d\text{-}i}$ is the length of the backup route from source/destination node to the intermediate node. Recovery time of connection can be classified into two phases: connection setup message time (TCS) and acknowledge time (TACK).

$$RTHSE\text{-}SPP = D_f + TCS + TACK \tag{3.3}$$

TCS and TACK are given in equations 4 and 5 below. Connection setup message time is the time when both the connection setup messages reached the intermediate node. In other words, the setup time of the later arrived message is considered a connection setup time. Let Tsetup,s-i and Tsetup,d-i are the connection setup times of source node to the intermediate node and destination node to intermediate node, respectively.

$$Tsetup,s\text{-}i = ns\text{-}i \times (MPCS + Cx) + \ell_{s\text{-}i} \times PT\ ,\ Tsetup,d\text{-}i = nd\text{-}i \times (MPCS + Cx) + \ell_{d\text{-}i} \times PT \tag{3.4}$$

$$TCS = Max\ \{ Tsetup,s\text{-}i\ ,\ Tsetup,d\text{-}i \} \tag{3.5}$$

Let Tack,s-i and Tack,d-i are the acknowledgment times from intermediate node to source node and intermediate node to destination node, respectively.

$$Tack,s\text{-}i = ns\text{-}i \times MPAK + \ell_{s\text{-}i} \times PT,\ \ Tack,d\text{-}i = nd\text{-}i \times MPAK + \ell_{d\text{-}i} \times PT \tag{3.6}$$

$$TACK = Max\{ Tack,s\text{-}i\ ,\ Tack,d\text{-}i \} \tag{3.7}$$

<u>Algorithm 3.1 for proposed halfway signal exchange –shared path protection (HSE-SPP)</u>

Consider a given network G (N, L, F), with N numbers of nodes, L links, and every link with frequency slots F.

N_r: Number of Connection requests

R (s, d, f): number of connection request with the source (s), destination (d), and the demand of frequency slots (f)

$P^j_{s,d}$: Primary light path from source(s) to destination(d), for connection request R_j

$B^k_{s,i}$: Backup light path from source (s) to an intermediate node (i), for connection request R_k

$B^k_{d,i}$: Backup light path from destination to an intermediate node (i), for connection request R_k

S_P: Spectrum assignment for the primary route

S_B: Spectrum assignment for the backup route

For primary route

1: connection request accepted $\leftarrow$ 0, Bandwidth accepted for the route
2: Connection request accepted $\leftarrow$ 0
3: For j $\leftarrow$ 1 to N_r do
4: Search for the primary route $P^j_{s,d}$ for R_j from S_P
5: If $P^j_{s,d}$ is available then
6: Bandwidth accepted $\leftarrow$ Bandwidth accepted + f_j
7: Allocate FS to the primary route
8: Connection request accepted $\leftarrow$ Connection request accepted + 1
9: end if
10: end for

For backup route

11: Bandwidth recovered $\leftarrow$ 0
12: Bandwidth failed $\leftarrow$ 0, bandwidth for the route
13: for j $\leftarrow$ 1 to L do
14: N_rFR^j number of connection request failed, when j^{th} link is considered
15: For k $\leftarrow$ N_rFR^j do
16: Bandwidth failed $\leftarrow$ bandwidth failed $+f_k$
17: Search for backup route $B^k_{s,i}$ and $B^k_{d,i}$ for R_k from S_B
18: if $B^k_{s,i}$ and $B^k_{d,i}$ is available then
19: Bandwidth recovered $\leftarrow$ Bandwidth recovered $+f_k$
20: end if
21: end for
22: end for

3.5 System Model

In this section, the definition and notations are presented. Let us consider N nodes, L link, and F frequency slots in the network. R is a set of connection requests for connection establishment. Ƥ and B are the sets of the primary and backup routes of the connection requests.

3.5.1 Notations

n	a network node $\forall n \in N$
ℓ	network link $\forall \ell \in L$
f	a frequency slot $\forall f \in F$
r	a connection request, $\forall r \in R$
p	a primary route, $\forall p \in Ƥ$
b	a backup route $\forall b \in B$
B	Backup route
ℓ^f	f^{th} frequency slot on link ℓ
ℓ_p^f	fth frequency slot of link ℓ assigned *pth* primary route
ℓ_b^f	fth frequency slot of link ℓ assigned to *bth* backup route
RT_r	Recovery time of request r, $\forall r \in R$
RTC	Recovery time constraint

3.5.2 Network constraints

In this section, different networking constraints are presented which are considered at the time of survivable network design.

3.5.2.1 Maximum capacity of the link

The number of frequency slots on the link always less than or equal to the maximum FSs available on the link.

$$\sum_{\forall f \in F} \ell^f \leq F, \ \forall \ell \in L \quad (3.8)$$

3.5.2.2 Spectrum continuity constraint for the primary and backup route

In continuity, the same frequency slot of each link must be assigned to the route.

(i) For primary route:

$$l_{i_P}^{f} - lf_{j_P}^{f} = 0,\ \forall i \neq j, \forall f \varepsilon F,\ \forall p \varepsilon P, \forall l \varepsilon L \tag{3.9}$$

(ii) For backup route:

$$l_{i_b}^{f} - l_{j_b}^{f} = 0, \forall i \neq j, \forall f \varepsilon F, \forall b \varepsilon B, \forall l \varepsilon L \tag{3.10}$$

3.5.2.3 Spectrum contiguity constraint for the primary and backup route

In contiguity, contiguous frequency slots must be assigned therefore the difference in indexing of first and last frequency slots of link always less than one of the numbers of frequency slots demand. Let us consider FD is the number of frequency slot demand arrives.

(i) For primary route:

$$l_P^{f_i} - l_P^{f_j} = FD - 1, \forall i \neq j, \forall f\ \varepsilon\ F, \forall p\ \varepsilon\ P,\ \forall l\ \varepsilon\ L \tag{3.11}$$

(ii) For backup route:

$$l_b^{f_i} - l_b^{f_j} = FD - 1, \forall i \neq j,\ f\ \varepsilon\ F, \forall b\ \varepsilon\ B, \forall l\ \varepsilon\ L \tag{3.12}$$

3.5.2.4 Recovery time constraint

Recovery time constraint is the maximum time for connection re-establishment after the failure.

$$\mathrm{RT_r} \leq \mathrm{RTC} \tag{3.13}$$

3.6 Discussion on Network Parameters

The simulation was done on MATLAB 2015 version with operating window 10, Intel Core i5 1.80GHz, with 8GB RAM. The connection requests are generated arbitrarily by considering two topologies that is ARPANET and COST239 topology having 20 nodes, and 32 links and 11 nodes, and 26 links shown in Fig.3.2 (a) and (b) respectively.

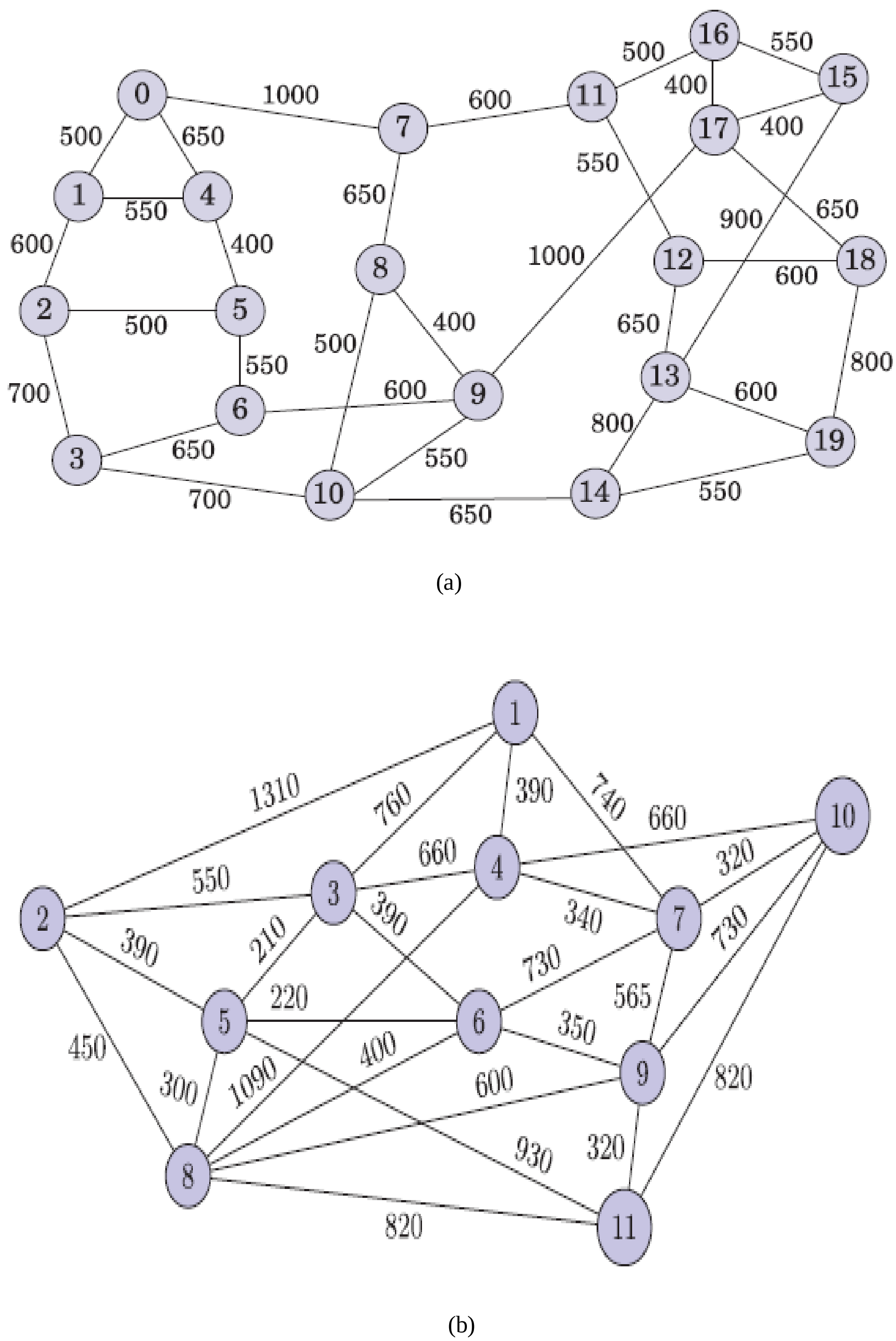
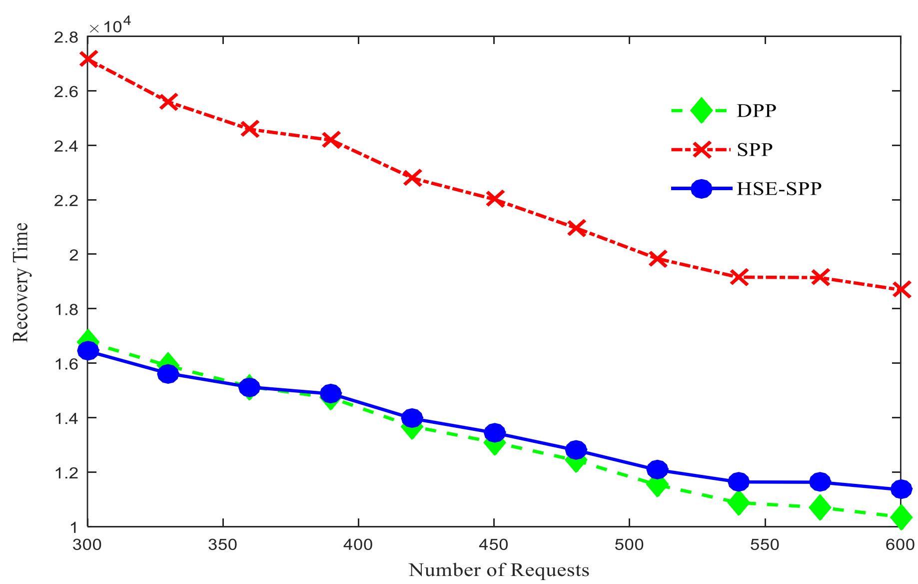


Figure 3.2 (a) ARPANET, (20 nodes and 32 links)   (b) Cost 239, (11 nodes and 26 links)

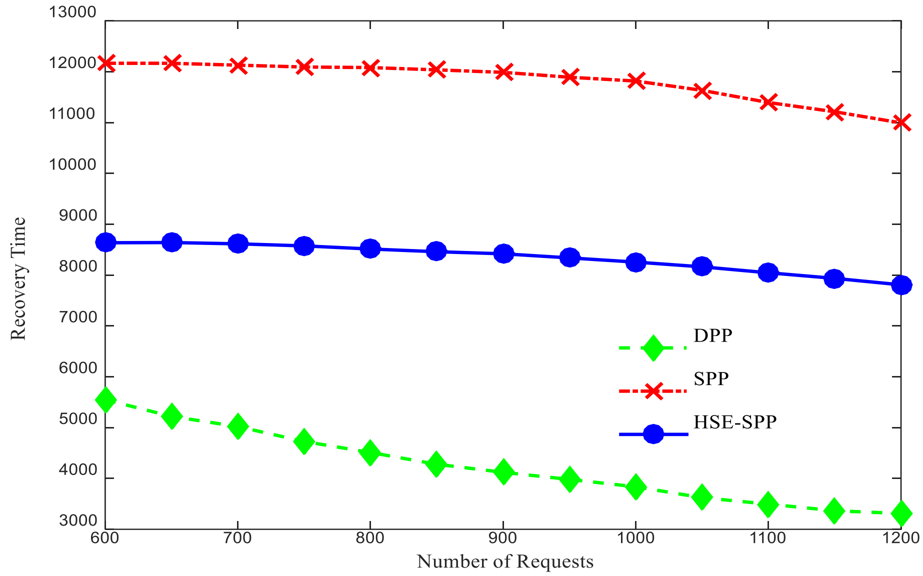
The connection requests are generated randomly with heterogeneous frequency slots between 1-8. All the survivable strategies are proactive where the protection path is pre-decided at the time of connection setup. Furthermore, a path-based backup route is assigned to the demanded request [10, 16]. In path-based, the backup route contains neither intermediate node nor links of the primary route. Both primary and protection routes must pursue spectrum continuity, and contiguity constraints [38]. Moreover, the connection is accepted only when the backup route satisfies connection recovery constraints. For route K (=3) shortest path routing is used. The performance of all three strategies is evaluated under four network parameters given below.

3.6.1 Connection recovery time

Connection recovery time is the time between the instants of the connection recovery process initiated and the acknowledgment received. After the occurrence of failure, the re-establishment of communication must be as soon as possible. Therefore, connection recovery time must be low for rapid connection establishment. In order to achieve fast connection recovery, a recovery time constraint has been introduced. In Fig. 3.2 (a) and (b) the recovery time constraints (RTC) are 45 and 21 ms for ARPANET and COST239 topologies, respectively.



(a)



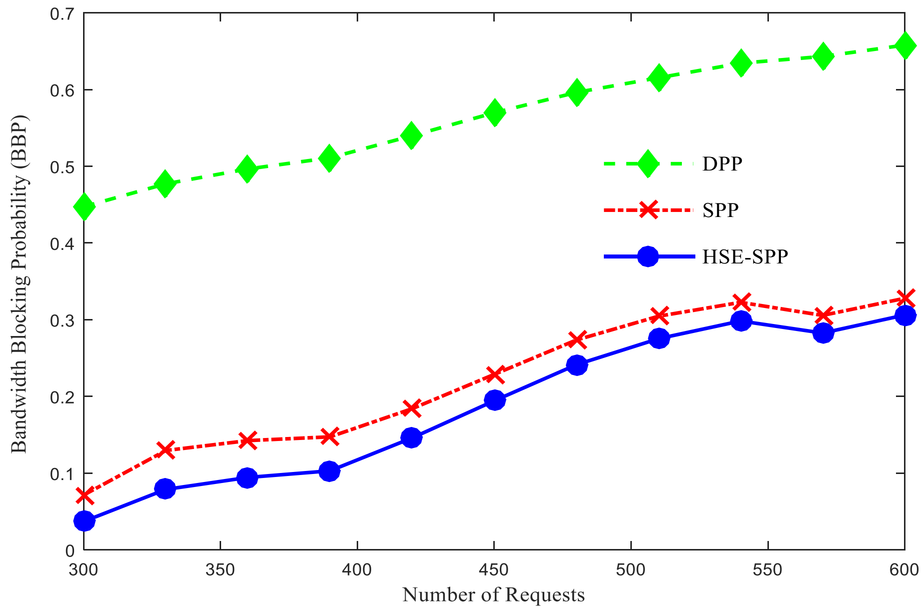
(b)

Figure 3.3 (a) Recovery Time in microseconds vs. Number of requests for ARPANET (b) Recovery Time in microseconds vs. number of requests for COST239.

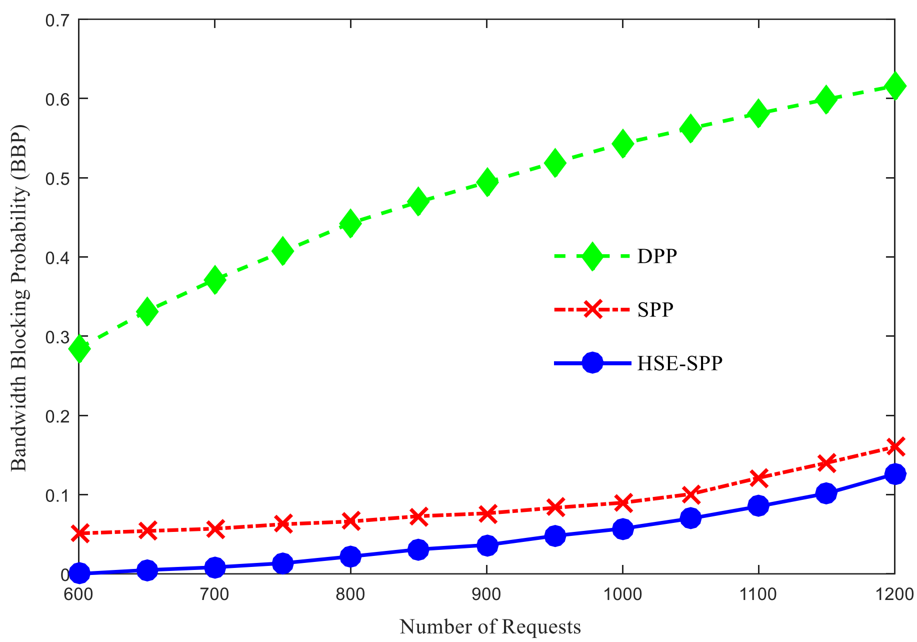
The values of different parameters considered for simulation are provided in Table 1. Figure 3.3 (a)-(b) shows the connection recovery time when a number of connection requests increases. In the ARPANET topology, recovery time is almost equal to DPP, while it is much lower than the SPP. And in the case of COST239, recovery time is between DPP and SPP strategies. Since in the ARPANET network backup routes are longer, therefore, the performance of HSE-SPP is comparable to DPP. Hence, HSE-SPP performs better when backup routes, are longer. In Table 1 for the comparison average recovery time is mentioned.

3.6.2 Bandwidth blocking probability (BBP)

BBP is one of the network parameters for evaluating the performance of the existing and proposed strategies. BBP is defined as the ratio of the total number of bandwidths rejected to the total number of bandwidth demanded [17, 38]. Connection request rejects either of the primary and backup routes unavailable. BBP must low under the given network constraints. Fig. 3.4 (a) and (b) mentioned bandwidth blocking probability (BBP) of recovery strategy with the number of connection demands for ARPANET and COST239 topologies, respectively.



(a)



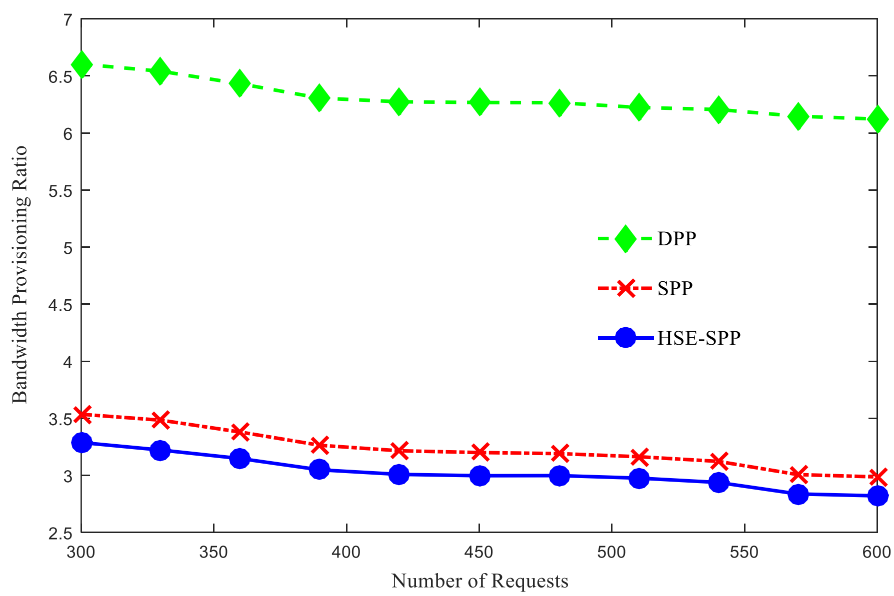
(b)

Figure 3.4 (a) Represents the variation in BPP vs. the number of requests for ARPANET (b) Shows the BBP vs. Number of requests for COST 239.

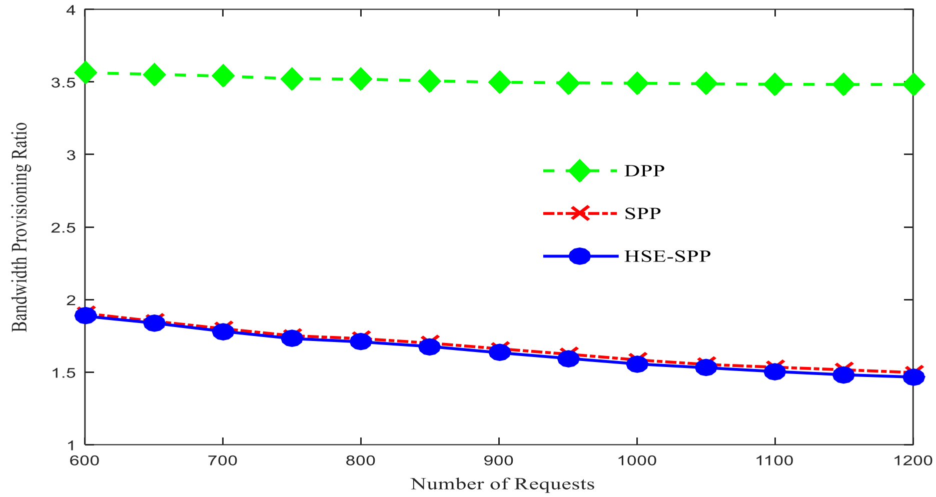
When the number of connection requests less, network resources are large enough for the establishment of connection requests, which results low BBP. As the connection request increases, BBP also increases due to the network resources crunch. Among all the three strategies, Our proposed halfway signaling exchange shared path protection (HSE-SPP) strategy has lower bandwidth blocking probability compared to shared path protection (SPP) and dedicated path protection (DPP). Although proposed HSE-SPP and SPP uses backup multiplexing for resource sharing, but in SPP connections are rejected due to connection recovery constraints. On the other hand, network resource utilization is inefficient in DPP due to higher redundancy backup resources results the highest BBP. The average BBP for ARPANET topology in our proposed strategy HSE-SPP is 0.1870, and for SPP and DPP are 0.2216, and 0.5626 respectively. Furthermore, COST239 are 0.0464, 0.0873, and 0.4786 for HSE-SPP, SPP, and DPP, respectively.

3.6.3 Bandwidth provisioning ratio (BPR)

In order to evaluate an average number of FSs assignment for the establishment of a frequency slot demand, we computed BPR. BPR is defined as the ratio of the total FS used to the total FSs accepted in the network. In HSE-SPP and SPP, backup resource sharing is increasing with the connection requests, thereby BPR decreases as mentioned in Fig.3.5 (a) and (b).



(a)



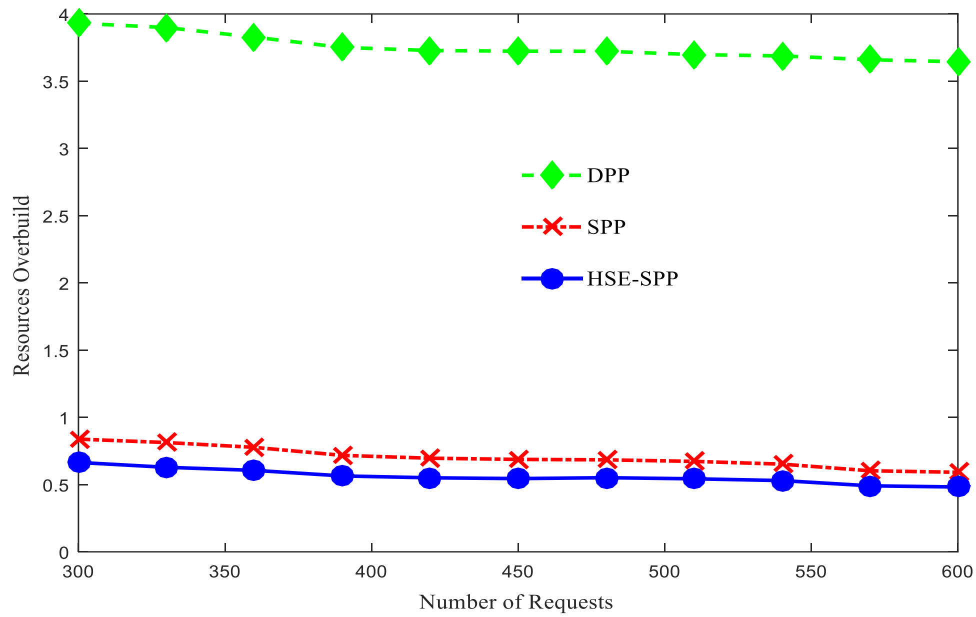
(b)

Figure 3.5 (a) Bandwidth provisioning ratio (BPR) vs. Number of Requests for ARPANET. (b) Represents the BPR vs. Number of Requests for COST239.

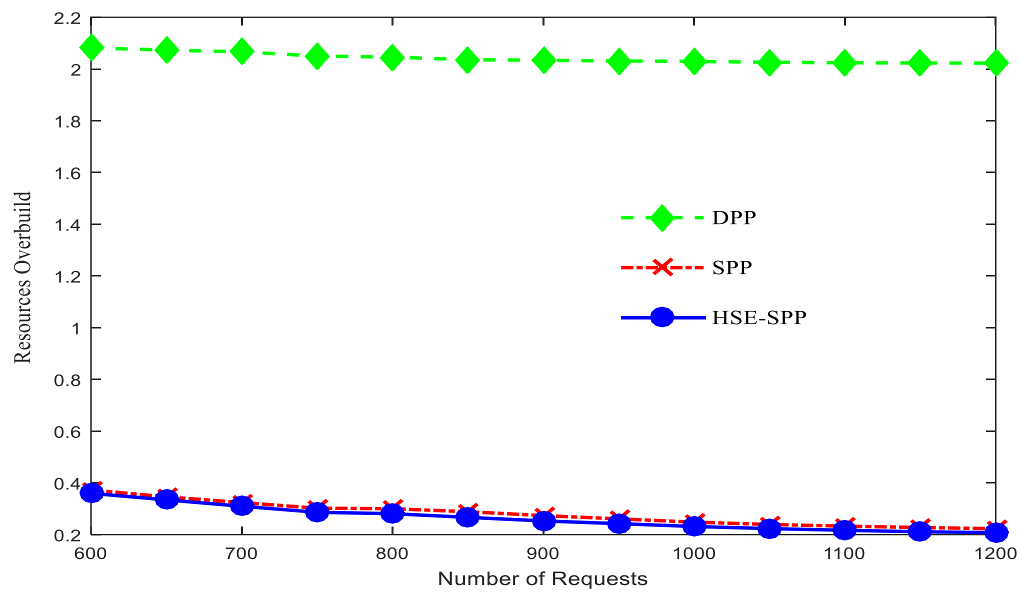
For DPP at a high number of connection requests, shortest routes are only accepted because the possibility of resources available on longer routes becomes very less. As a result, BPR decreases. The average bandwidth provisioning ratio for ARPANET topology in our proposed HSE-SPP is 3.0255 and for SSP and DPP are 3.2316 and 6.3072 respectively and the average of BPR for COST239 is 1.6453 for HSE-SPP and for SPP and DPP are 1.6697 and 3.5090 respectively.

3.6.4 Backup resource overbuild ratio

Backup resource overbuilds measure how much redundancy backup FSs are needed over per frequency slot acceptance. It is defined as the ratio of the total FS used by the backup route to the total number of FS accepted. In HSE-SPP and SPP overbuild ratio is low due to backup resources sharing, while in DPP resources overbuild is high. Figure 3.6 (a) and (b) shows that our proposed strategy has a low overbuild ratio as compared to SPP and DPP for ARPANET and COST239 topologies.



(a)



(b)

Figure 3.6 (a) Resource overbuild ratio vs. Number of Requests for ARPANET (b) Resource overbuild ratio vs. Number of Requests for COST239.

The average backup resource overbuild ratio (BROR) for ARPANET topology for HSE-SPP, SPP and DPP are 0.5596, 0.7028, and 3.7520, and for COST 239 are 0.2633, 0.2799, and 2.0418 respectively.

3.7 Summary

In this chapter, a halfway signaling exchange mechanism for fast recovery is proposed. In the proposed HSE-SPP scheme, the source and destination node simultaneously send the connection setup message to the intermediate node. After establishing the connection the intermediate nodes send the confirmation message to the source and destination node respectively. The network parameters such as recovery time, BBP, BPR, and resources overbuild ratio are evaluated for survivability of the optical network. Our simulated results are better than the existing SPP and DPP schemes.

CHAPTER 4

RESOURCE EFFICIENT RECOVERY SCHEME FOR ELASTIC OPTICAL NETWORKS

In this chapter, two existing topologies are considered that's COST239 and NSFNET, and find the backup route for the arbitrarily generated connection request. Here, we proposed a path-based recovery scheme for a single link failure in the elastic optical network. Our proposed strategy reduces the rejection of connection requests. We evaluate the performance of some network parameters Such as bandwidth blocking probability (BBP), network capacity utilization (NCU), and recovery time in the MATLAB simulator. The traffic congestion in our proposed path-based recovery scheme (PBRS) is lower as compared to dedicated path protection (DPP) and shared path protection (SPP) and the utilization of the backup resources is better as compared to DPP and SPP.

4.1 Introductions

As the number of internet users increases in the last few years, the use of different applications such as video conferencing, high definition televisions, and multicasting are also increased, which require more bandwidth. The existing wavelength division multiplexing (WDM) fixed grid cannot meet the futures higher bandwidth demand, where the wavelength spacing is 50GHz, the bit rates are 10 Gbps, 40 Gbps, and 100 Gbps. If a client requires lower bandwidth for the data transmission and the channel space allotted is 50 GHz as per international telecommunication union (ITU) standard, the rest of the spectrum gets wasted. According to Tele Geography, the bandwidth demand up to 2020 is expected to about 1,103.3 Tb/s [87]. Hence the optical networks are required to fulfill this future higher bandwidth requirement [43]. The spectrum sliced elastic optical network (SLICE) is a suitable replacement for a conventional fixed WDM grid. The network which uses orthogonal frequency division multiplexing (OFDM) is called the elastic optical network (EON), or flexible optical network (FON). The EON divides the spectrum size as 6.25, or 12.50 GHz or more [43], the bandwidth variable transponder (BVT) is used and it ranges from 10Gbps to 200Gbps. The BVT is used in EON to tune the bandwidth for regulating the transmission bit rate or modulation format. The BVT supports a very high data rate by using different modulation formats such as 64-quadrature amplitude modulation (QAM) used for a shorter distance, 16-QAM, and binary phase-shift keying (BPSK) used for longer distance [27]. The EON has the ability to meet the future client bandwidth requirement. In EON the efficiency and utilization of the network are greatly improved. There are few resemblances between the WDM and EON, the new challenges in EON are due to their flexibility.

EON has so many properties like flexibility in data rate, low power consumption, low signal distortion, low signal attenuation, low cost, and small space requirement. In EON routing and spectrum, assignment finds an unused frequency slot (FS) [87] [88] to meet the traffic demand and set up a light path connection. The allotment of the spectrum in EON is in a contiguous manner. As, the connection request acceptance rate increases, bandwidth blocking probability (BBP) reduces. The main constraint in the spectrum assignments is spectrum continuity, spectrum contiguity and spectrum non-overlapping. The spectrum continuity constraint needs the allotment of similar FS to every fiber along the light path. The spectrum contiguity constraint requires the allotment of FS to the light path is consecutive. The non-overlapping constraint allows any FS to the light path.

The failure of any link due to a fiber cut a single or multiple failure or node failure in the optical network results in more data loss and also affects the Quality of Services (QoS). The survivability in EON can be improved by using various techniques [20] [89]. The rerouting of data from the failed link to the alternate route is the common recovery scheme in the optical network. This alternative backup route may be provisioned at the time of connection setup or it is dynamically searched after the failures occurred. There are two types of resource recovery schemes, one is advance reservation (AR) and other is immediate reservation (IR), in AR the backup resources are reserved in advance at the time of connection setup, whereas in IR the alternate backup route is dynamically searched after the failure information received at the source node [90] [91].

The recovery time for the arbitrary generated source (s) – destination (d) connection request for two existing topologies viz. COST239 and NSF network. The s-d request for these two topologies is to be generated by using n (n-1) / 2, n be the nodes number in the network.

4.2 Related Work

There is much literature available for the survivability of EON. The first and last fit strategy for the survivability of failure in EON for the primary route and spectrum allocation has been discussed in [27] [87]. The RSA problem in EON with BVT is discussed in [43]. The advance reservation (AR) and Immediate reservation (IR) protection schemes are provided in [89]. The mixed-integer linear programming (MILP) for DPP is presented in [91] and the comparison with SPP is explained in [92]. The multi-layer recovery, spectrum sharing, energy efficiency failure, and blocking probability for the shared path protection scheme is discussed in [78]. The comparison between SPP and DPP are discussed in [90]. The Shared Backup Path Protection (SBPP) with RSA for EON are presented in [59].

The more dedicated recovery strategy for the failure in EON is presented in [62]. The dedicated protection scheme for EON by using ILP is discussed in [77]. Metaheuristic approach which includes Tabu Search Based Algorithm (TS) and an Adaptive Frequency Assignment (AFA), which provide nearly optimal solutions for large simulations are discussed in [93]. There are many heuristic algorithms that have been proposed which include Adaptive Frequency Assignment (AFA) with SBPP. The comparisons between SBPP and DPP with ILP formulation with or without variable transponders are provided in [92], which shows that the SBPP and variable transponder improve the performance in EON. The hybrid protection algorithm also called hybrid protection light path which defines the power consumption and resource availability that has been proposed in [94] for EON. For every request, the shortest backup path with minimum resource utilization has been selected. The inter-data transmission services for EON and an ILP model and heuristic algorithm are proposed to solve the routing and spectrum allocation problems, that improve the resource utilization ratio are provided in [95].

The recovery after the failure of the primary route has been explained in [96]. The multipath restoration strategy has been presented in [83]. The recovery of multilink failure based on load awareness is discussed in [74] and the survivable algorithm is discussed in [30]. The restoration in EON is presented in [66] and provides better resource utilization as compared to the protection scheme. Multipath recovery has been discussed in [97]. P-cycle restoration is presented in [98] provides a 100% recovery against single link failure.

4.3 Existing Strategies

In this chapter, we addressed a SPP and DPP and an efficient recovery scheme for failure in the optical network.

4.3.1 Notations Used

Here, the failure of the link is detecting by the adjacent node. The various parameters are used for the protection switching time such as message processing time, optical connect and propagation delay in the network, etc. are given below.

- The message processing time at a node, M_t is 10 µs.
- The delay in signal propagation is d_p of each signal on the link is 400 s, which corresponds to 80 km length.
- Optical cross-connects, Co does not have any fixed values, and it takes as 10 ns, 10 ms, 10 s and 500 s.
- The F_t, is failure detection time, is about 10 µs.
- The number of hops l_h, the node adjacent to link failure to the source and destination node.
- The number of links l_b, for the backup path from source to the destination node.

Let G (V, E, F) represents the network topology (Nodes, Links and frequency slot) and different notations are as follows:

v	Set of the nodes $\forall$ v ϵV
e	Set of the Links $\forall$ e ϵE
f	Set of frequency slot for each link

s Source node

d Destination node

r Connection request ∀ r ϵR , that is {(s1, d1), (s2, d2)….(si, di)} where ∀(s,d)ϵV, ∀s≠d, ∀ iϵV.

Pi Primary route, of the ith connection request, where ∀ iϵR.

Bj Backup path, of the jth connection request where ∀ jϵR.

4.3.2 Shared Path Protection (SPP)

In this scheme, the nearby node of the failed link detecting the link failure and sends the link failure message to the source node and the end node. Then the source node sends a connection setup message to the receiver node and the optical cross-connects organize all nodes for the backup path protection, at the time of connection establishment the backup path is reserved in advance. The optical cross-connects are not configured to allow for the sharing of backup wavelengths. The end node after receiving the connection setup message sends a confirmation message to the source node. For completing connection setup the total time is

$$T_{SPP} = F_t + l_h \times d_p + (l_h+1) \times M_t + (l_b+1) \times Co + 2 \times l_b \times d_p + 2 \times (l_b+1) \times M_t \qquad (4.1)$$

4.3.3 Dedicated Path Protection (DPP)

In DPP, the adjacent node to the failure link sends the link failure message to the source and receiver node. Then the source node sends a connection setup message to the end node by a backup path that is reserved in advance at the time of connection establishment and also the optical cross-connects are configured at the time of connection setup and not required at the time of connection switching time. The response of the DPP is slower as compared to our proposed scheme. The total switching time for the DPP is

$$T_{DPP} = F_t + l_h \times d_p + (l_h + 1) \times M_t + 2 \times l_b \times d_p + 2 \times (l_b + 1) \times M_t \qquad (4.2)$$

4.3.4 Our Proposed Path-Based Recovery Scheme (PBRS)

In this scheme, the nearby node of the failure link provides the notification message to the source and user end node, and then immediately the source node establishes a backup path to the end node.

The recovery time for the proposed scheme is

$$RT_{PBRS} = F_t + l_h \times d_p + T_c + T_a \tag{4.3}$$

RT_{PBRS} be the recovery time for the proposed path-based recovery scheme (PBRS) and T_c and T_a be the connection setup time from source to destination and acknowledge time from the destination to source. We assume n_s-d be the nodes on the backup route from source to destination and n_d-s be the nodes from destination to source node and l_{s-d} be the length of the backup route from source to the destination and l_{d-s} be the length of acknowledgment from destination to source node. T_{s-d} and T_{d-s} be the connection setup time from source to destination and destination to source.

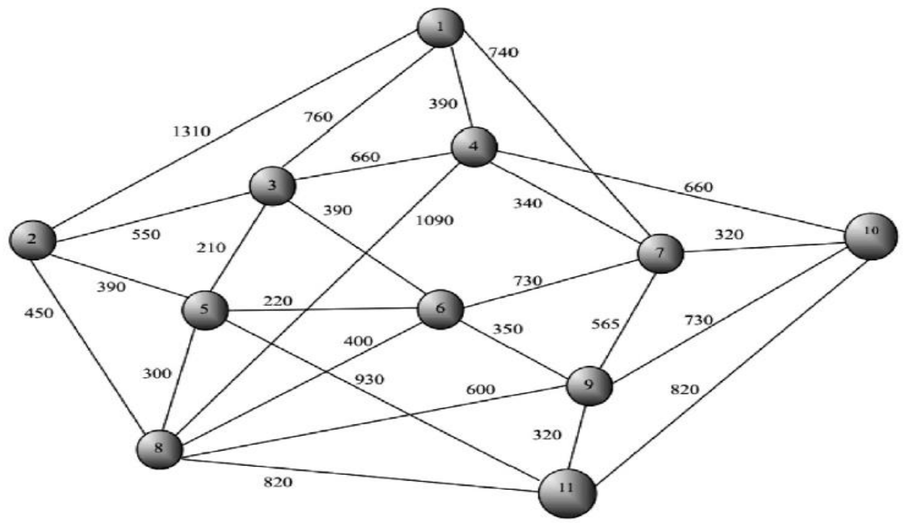
$$T_{s-d} = n_{s-d} \times (M_t \times C_o) + l_{s-d} \tag{4.4}$$

$$T_{d-s} = n_{d-s} \times M_t + l_{d-s} \tag{4.5}$$

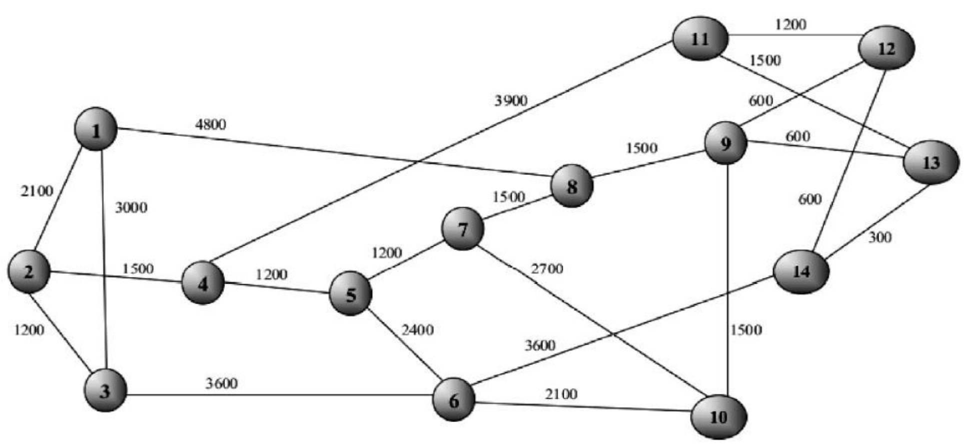
Hence, $T_c = T_{s-d}$ (4.6)

$$T_{a,d-s} = n_{d-s} \times M_t + l_{d-s} \tag{4.7}$$

$$T_a = T_{a,d-s} \tag{4.8}$$



(a)



(b)

Figure 4.1 (a) COST 239 (11Nodes & 26 Links)   (b) NSFNET (14 Nodes & 22 Links).

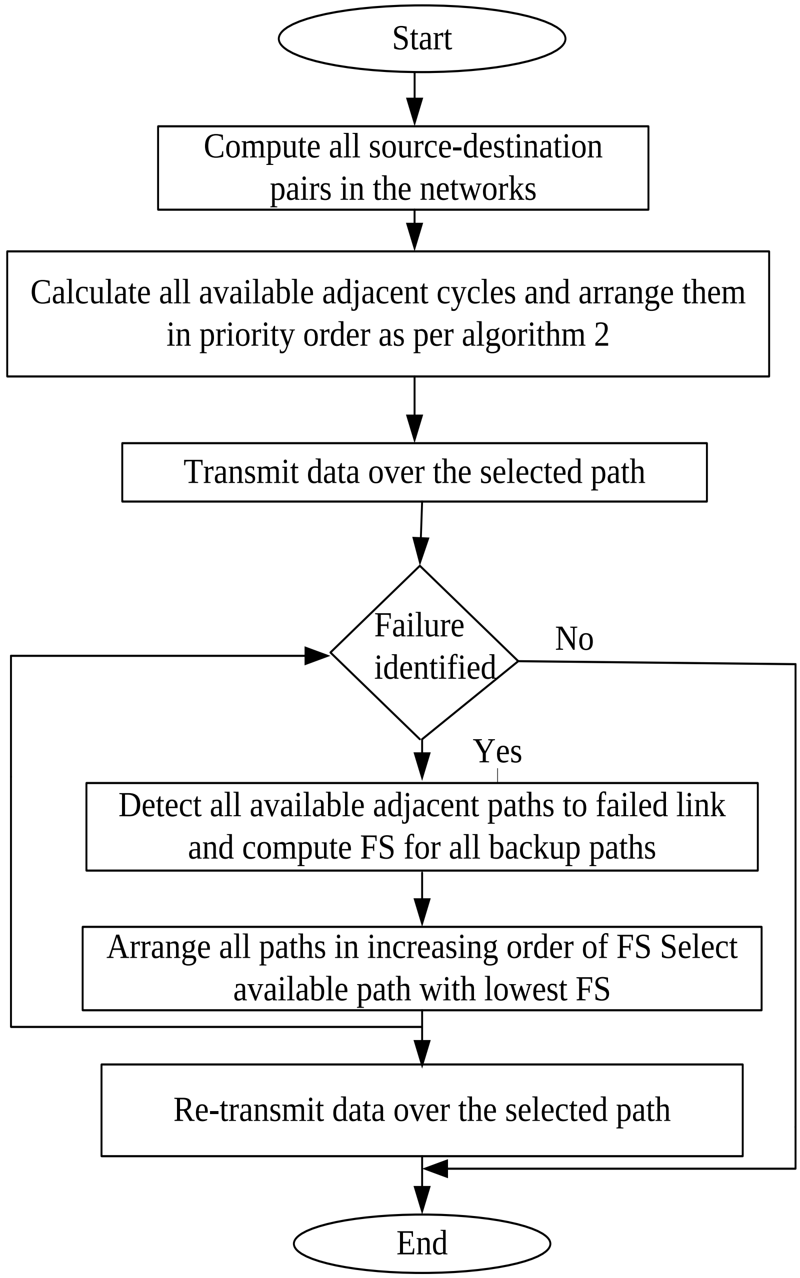


Figure 4.2 Flow chart for path-based recovery scheme for a single link failure in the elastic optical network.

Algorithm 4.1 for Path-based recovery scheme (PBRS)

For working route

1: Connection request accepted $\leftarrow$ 0, Bandwidth accepted for the route

2: Connection request accepted $\leftarrow$ 0

3: For $i \leftarrow$ 1 to r do

4: Search for the primary route $P^{i}_{s\text{-}d}$ for R_i from S_P

5: If $P^{i}_{s,d}$ is available then

6: Bandwidth accepted = Bandwidth accepted + f_i

7: Allocate FS to the primary route

8: Connection request accepted = Connection request accepted + 1

For backup route

9: Bandwidth recovered $\leftarrow$ 0

10: Bandwidth failed $\leftarrow$ 0, bandwidth for the route

11: for $i \leftarrow$ 1 to L do

12: For $j \leftarrow$ $r_f R^i$ do

13: Accept the connection and allocate the resources to the connection request

14: Search for backup route $B^{j}_{s,d}$ for r_j from S_B

15: else

16: Connection recovered = connection recovered +f_j

17: end if

18: end for

19: end for

20: end for

4.4 Evolutions of Network Parameters

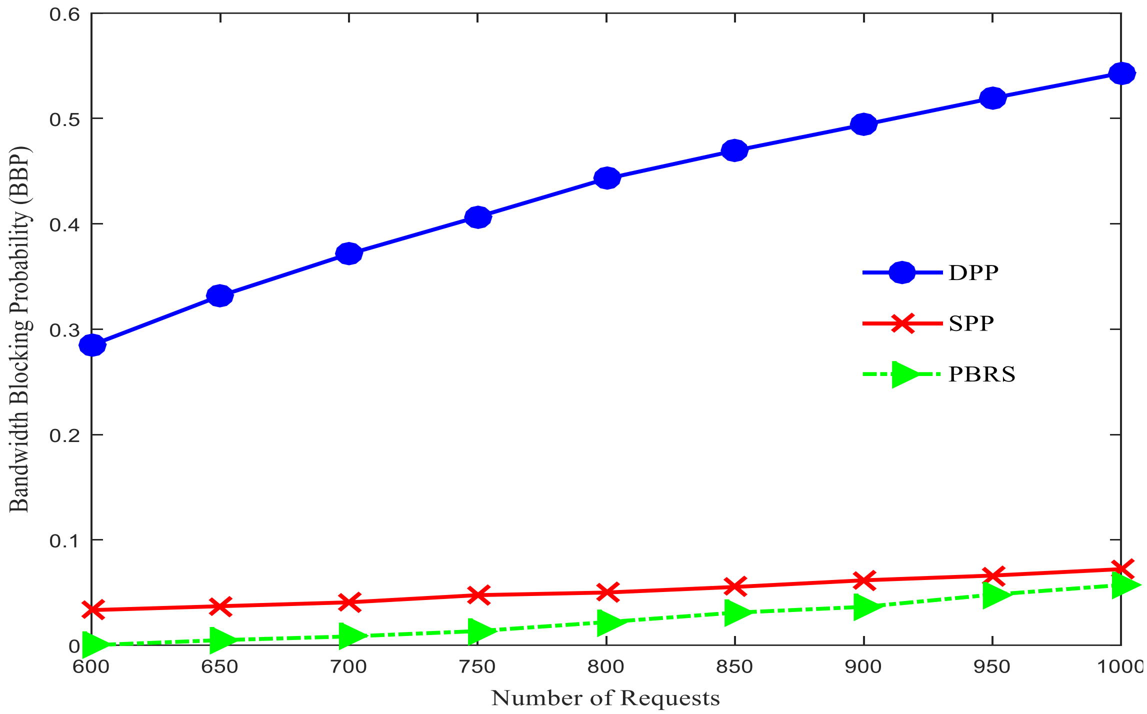
We evaluate the various network parameters in MATLAB 2018 on i5-7400 Intel® core(TM) 3GB system with 8GB RAM, by randomly generated source (s)-destination (d) requests. Figure 4.1 (a) and (b) show COST239 with 11 nodes and 26 links and NSFNET topologies with 14 nodes and 22 links respectively.

Table 4.1 the mean values of network parameters for different Strategies.

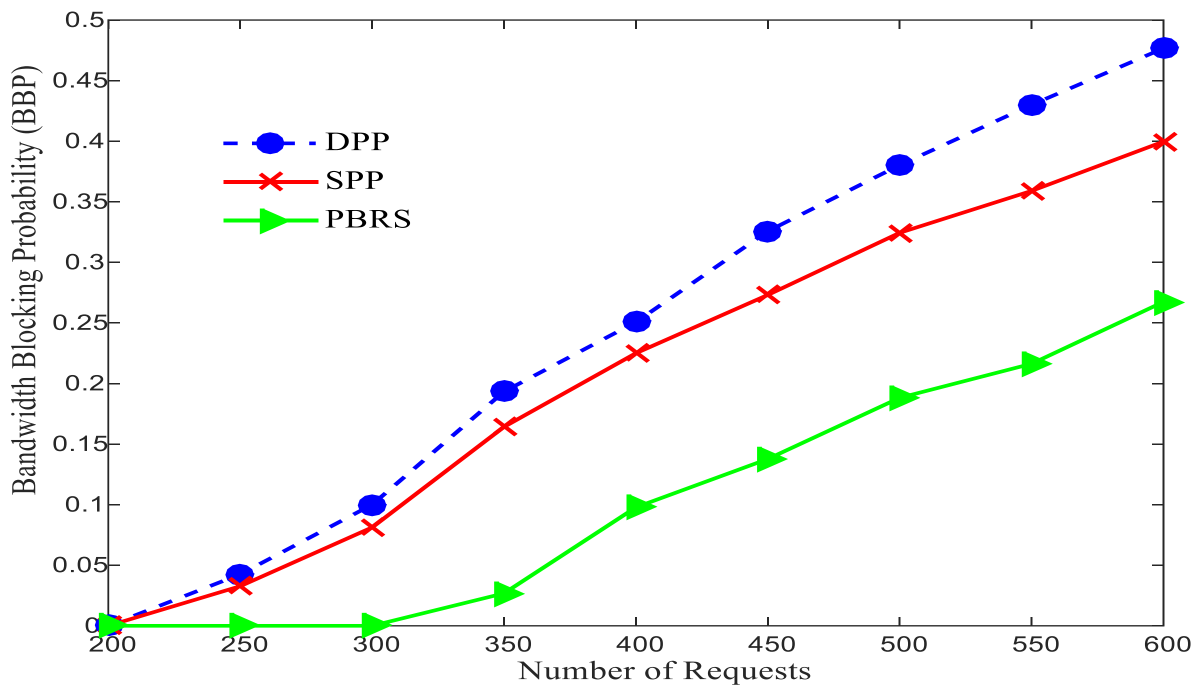
Network Parameters	**COST 239**			**NSFNET**		
	DPP	**SPP**	**PS**	**DPP**	**SPP**	**PS**
Recovery Time (ms)	4.58	12.3	8.49	42.8	55.4	38.0
BBP	0.4292	0.0515	0.0245	0.2444	0.2066	0.1038
NCU	45.2293	38.1105	37.9288	70.4041	66.8805	64.3185

4.4.1 Bandwidth Blocking Probability (BBP)

The BBP is defined as the ratio of the number of bandwidth requests rejected to the total bandwidth demanded [77]. It has been noticed from Figures 4.2(a) and (b) the BBP of our proposed strategy is very less as compared to the SPP. Hence, in our proposed strategy the large number of s-d requests accepted as compared to SPP. The mean BBP for our proposed PBRS, SPP, and DPP are 0.0245, 0.0515, and 0.4292 respectively for COST239, and the BBP for our PBRS, SPP, and for DPP is 0.1038, .0.2066, and 0.2444 respectively for NSF network. The rejections of the connection request in the NSF network are more than COST239. The mean values for different parameters are provided above in Table 4.1.



(a)

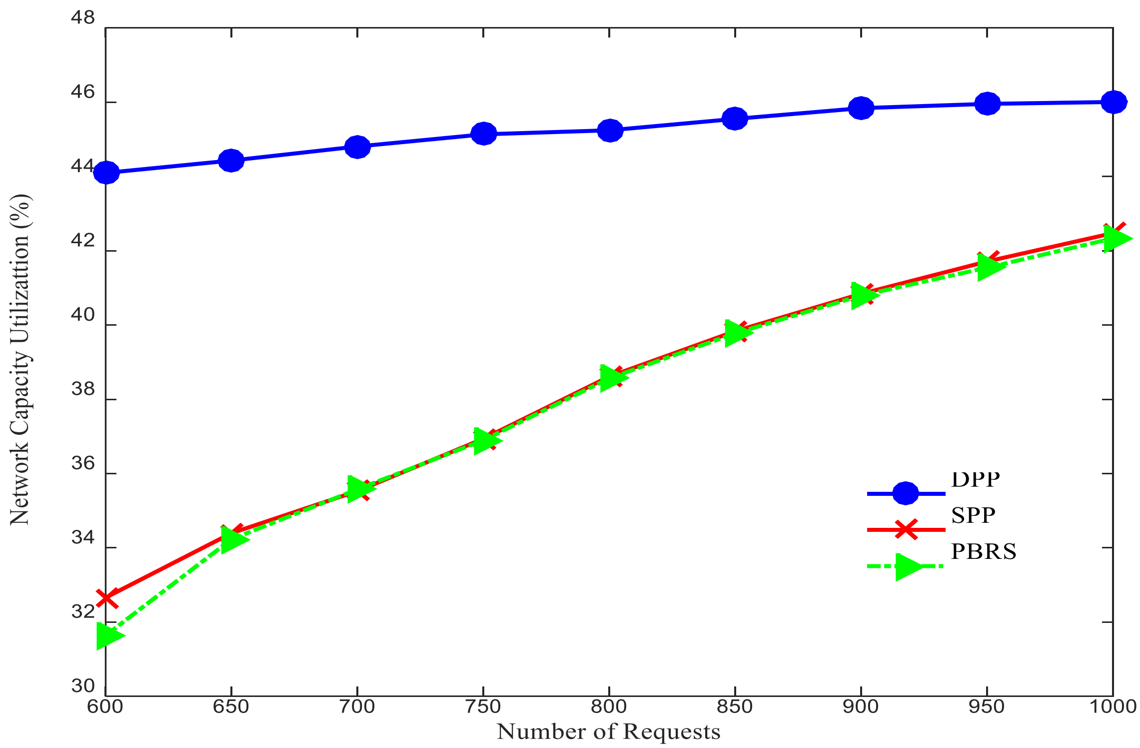


(b)

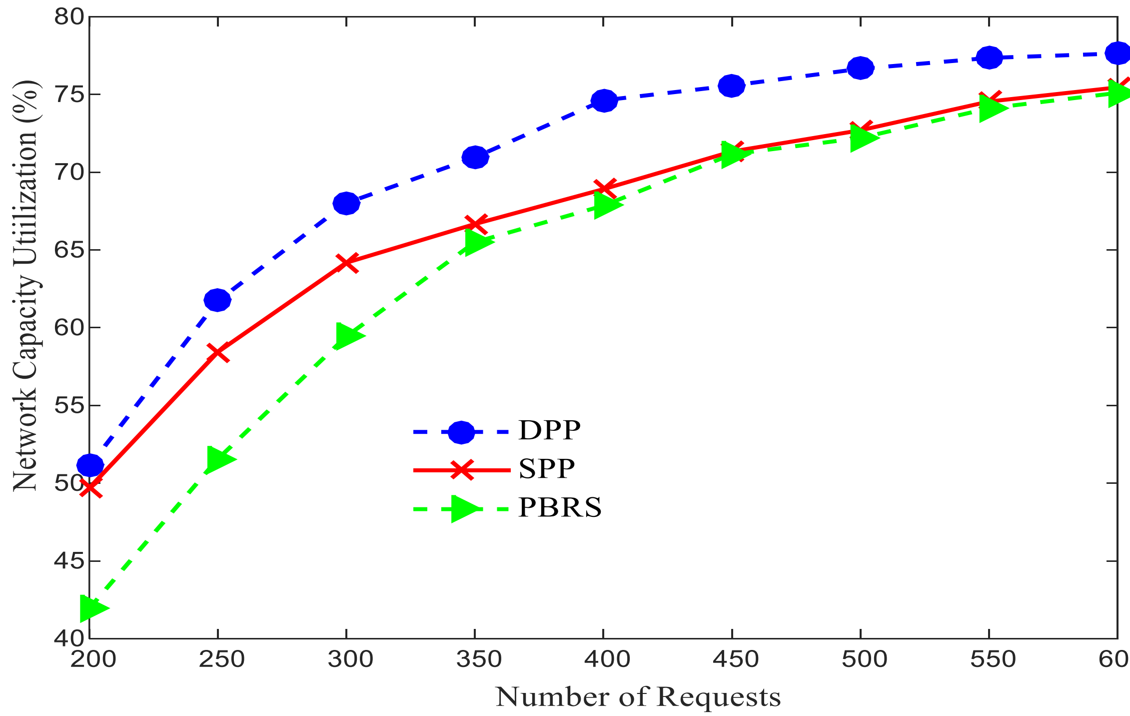
Figure 4.3 (a) Bandwidth blocking probability, (BBP) vs. no. of requests for COST239 (b) BBP vs. no. of requests for NSFNET.

4.4.2 Network Capacity Utilization (NCU)

The network capacity utilization ratio is defined as the ratio of the total spectrum used to the connection request accepted in the network. The average NCU for COST 239 is 45%, 38% and 37% for DPP, SPP and for our proposed scheme (PS) respectively, while for NSFNET DPP, SPP and for PS is 70%, 66%, and 64% respectively as given in Figure 4.3 (a) and (b). In NCU if 70% of the spectrum is used for traffic, then slowdown will occur in-network, if this slowdown remains for a long time than a long queue of traffic will occur in the network, which causes a holdup in the traffic. In COST239 the traffic is less as compared to the NSFNET.



(a)

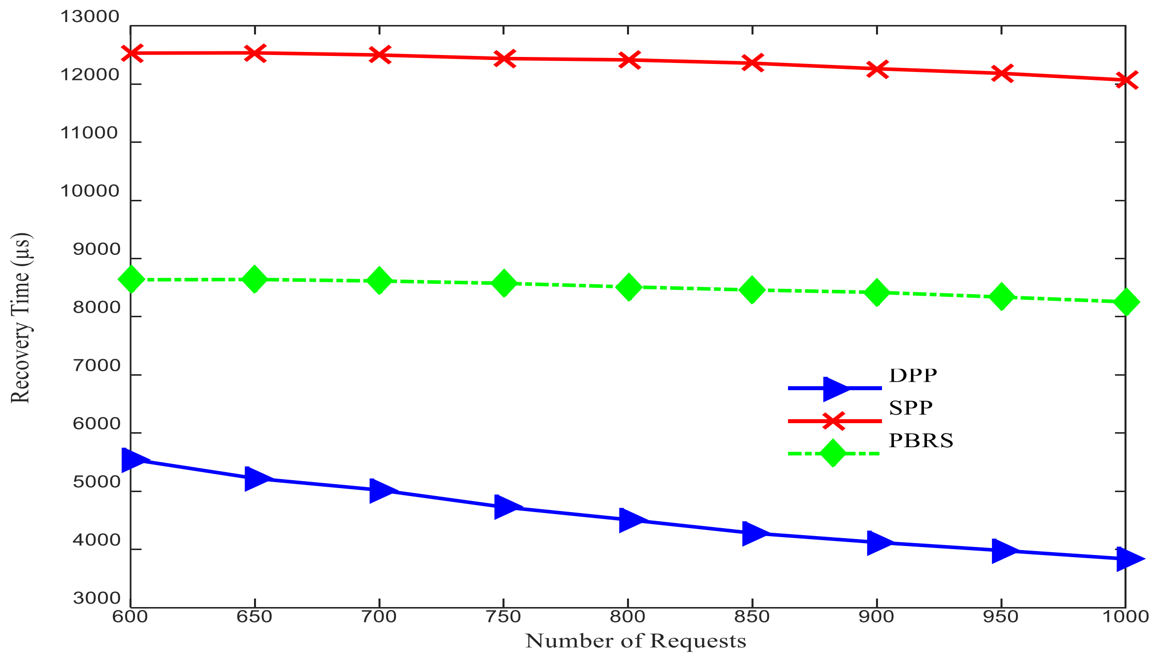


(b)

Figure 4.4 (a) Network capacity utilization, (NCU) vs. no. of requests for COST 239 (b) NCU vs. no. of requests for NSFNET.

4.4.3 Recovery Time (RT)

The RT is the time instant from where the recovery process is started and the confirmation message received from the destination to the source. For fast recovery, a recovery time constraint is required to introduce. Recovery time, in our proposed path-based recovery scheme, (PBRS) is less than SPP, and above than DPP as shown in Figure 4.4 (a) for COST239 and also for NSF network it's lower than SPP and DPP as mentioned in Figure 4.4 (b).



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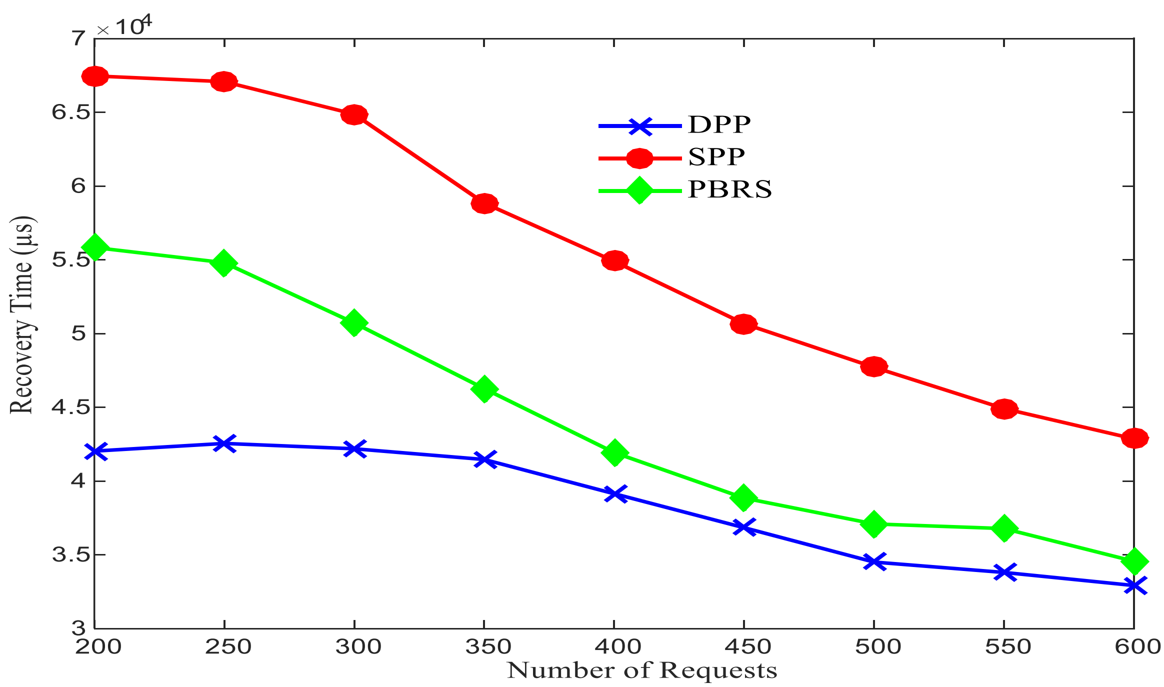


(b)

Figure 4.5 (a) Recovery time in microseconds vs. no. of requests for COST239 (b) Recovery time in microseconds vs. no. of requests for NSF network.

4.5 Summary

In this chapter, the proposed path-based recovery scheme (PBRS) scheme shows the recovery time between SPP and DPP. We evaluate parameters like BBP and NCU ratio for two topologies that are COST239 and NSF network. Our purposed strategy shows lower BBP and NCU than SPP and DPP for COST239 and NSFNET.

Hence, our PBRS is better in terms of resource utilization and recovery time.

CHAPTER 5

PROACTIVE LINK BASED SURVIVAL ELASTIC OPTICAL NETWORKS

In this chapter, a link-based fast connection recovery strategy has been explained. A backup path is either reserved in advance or searched dynamically after the failure occurred in the network. Both these recovery strategies required large backup capacity. Here, different network parameters for three topologies are analyzed that is COST239, ARPANET, and NSFNET, and compare the results for shared link protection (SLP), dedicated link protection (DLP), and our proposed link protection (PLP) scheme.

5.1 Introductions

With an increase in the number of internet users from the last few years correspondingly the requirement of bandwidth-intensive services such as online browsing of video, cloud computing, and online gaming, etc. The optical network plays an important role in the transmission of more information online.

The existing Optical networks used wavelength division multiplexing (WDM) for the transmission of more information online. This WDM scheme is based on the fixed bandwidth spectrum of 50GHz or 100GHz and fixed modulation formats [99]. This fixed grid cannot meet the demand for higher bandwidth. The EON is a new paradigm in the optical network, used to provide variable bandwidth as per user requirements [100]. EON provides granular fine frequency slots (FS). EON considers the FS continuity and contiguity constraint. The routing and spectrum assignment problem is also considered in EON [101]. The survivable networks have the ability to quickly restore the failure in EON [102]. This can be done by providing a spare capacity in the existing optical network. In literature, survivability is categorized into pre-protection and restoration schemes. Protection scheme reserve the alternate route for connection failure in advance, whereas the restoration scheme dynamically searches the backup after failure happened in the network. This scheme is more efficient than the protection scheme [87].

Many studied have been done for the protection of single link failure and double link failure. Guaranteed survivability has been provided in [103]. Dual-link failure recoverability is proposed in [29]. Recovery schemes for two-link failure are designed in [104] [105] [106] where the link disjoint alternate routes are available. All these schemes provide guaranteed protection [28]. Another approach to handle the two link failures is re-provisioning after the first failure (RAFF) [39]. In RAFF, every request is allocated an alternate route in the spare capacity for a link failure in the network.

After the recovery of the first failure, the new backup alternate routes are provided for unrecoverable failure. In this way, the affected request can be restored, using the new alternate backup route, when the second failure happened. In [107] p-cycle network is proposed, where the RAFF spare capacity can reconfigure dynamically.

The ILP model provided two cases, the first is whole cycle reconfiguration and the other is additional cycle configuration. Hence, alternate backup route provisioning after the recovery of the first failure, and before the second failure occurs. Thus, all connection demand whose primary paths are affected, by the first failure required to have a provision of the alternate protection path.

Here, a new proactive protection scheme to handle the single link failure [108]. Despite the protection scheme in which a request requires two backup routes for connection recovery, our proposed scheme requires only one backup route for each demand to save the spare capacity in the network. Our schemes compute the backup route for all requests which not protected after the second failure happened. The main idea of our proposed scheme is as follows: Each request has to be assigned a single backup route. The spare capacity is reserved in advance, for ensuring the entire request whose primary route is affected by second link failure and can be restored using the pre-planned protection path. The second is for those requests whose primary, and protection routes are affected by the second link failure, the restoration is used for the second link failure.

The proposed strategy uses a pre-planned protection strategy to provide a recovery to the single link failure and those are affected by the first link failure. For the request that is not recovered by the pre-planned protection are recovered by using a dynamic restoration scheme. Our proposed scheme has the advantage of a fully pre-planned backup path for each request. Also, our backup path reserved capacity exploits the backup path sharing under double link failure. Each primary path has DLP. Our simulation results show that the PLP provided better recovery as compared to SLP.

5.2 Protection Schemes

Here, we discuss the dedicated link protection (DLP), shared link protection (SLP), and our proposed link protection (PLP) schemes.

5.2.1 Notations Used

Here, failure of the link detecting by the adjacent nodes. The different network parameters are used for the switching protection, such as message processing time, optical cross-connects and the propagation delay in the optical network, etc. are given as follows.

- The processing time of the message m_p at the nodes is 10 µs.
- The delay due to signal propagation p_d for each signal is 400 s, which corresponding to 80 km length.
- Optical cross-connects, c_x takes any value that is 10 s, 10 ms, 10 ns, and 500 s.
- The f_d, is the failure detection time, is about 10 µs.
- l_h be the no. of hops/links, for the backup path from source to the destination node.

Let G (N, L, f_s) represents the network topology (Nodes, Links and wavelengths) and different notations are as follows:

n	Set of the nodes $\forall$ n∈N
l	Set of the Links $\forall$ l∈L
f_s	Set of FS for each link
t_s	Transmitting node
d_s	Destination node
r	Connection request $\forall$ r ∈R , that is {(s1, d1), (s2, d2)….(si, di)} where ∀(s,d)∈V, ∀s≠d, ∀i∈V.
p_r	Primary route of the ith connection request where ∀i∈R.
b_r	Backup route of the ith connection request where ∀i∈R.

5.2.2 Shared Link Protection (SLP)

In SLP, the nearest node of the failed link detects the failure of the link [26] and immediately established the connection with the receiving node by the alternate backup route. Here, the backup FS is reserved in advance. In SLP the optical cross-connects c_x is not allowed for the sharing of backup FS. The destination nodes send an acknowledgment when it receives connection setup message from the source node. The total time taken for connection establishment is

$$RT_{SLP} = F_d + (l_h+1)\times c_x + 2\times l_h \times p_d + 2\times(l_h+1)\times m_p \tag{5.1}$$

5.2.3 Dedicated Link Protection (DLP)

In this scheme, the nearby node establishes the connection between the failure link after detecting the failure by using advance reserved FS. The response of DLP is slower than our proposed link protection scheme (PLP).

The switching time for the DLP is

$$RT_{DLP} = F_d + 2\times l_h \times d_p + 2\times(l_h+1)\times m_p \tag{5.2}$$

5.2.4 Proposed Link Protection Scheme (PLP)

In this scheme, the nearby node immediately establishes the connection between the transmitting and receiving nodes.

The recovery time for the proposed link protection scheme is

$$RT_{PLP} = F_d + (l_h+1) + T_c + T_a \tag{5.3}$$

RT_{PLP} be the recovery time for the proposed scheme and T_c and T_a be the connection setup time between the adjacent node to the receiving node and acknowledgment time from receiving node to the link node. We assume $n_{sn\text{-}rn}$ be the nodes on the backup route between source node to receiving node. $T_{sn\text{-}rn}$ and $T_{rn\text{-}sn}$ be the connection establishment time from the source node to the receiving node and receiving node to the source node. T_c is the total connection setup time from the source node to the receiving node.

$$T_{sn-rn} = (m_p \times c_x) + l_{sn-rn} \tag{5.4}$$

$$T_{rn-sn} = n_{rn-sn} \times m_p + l_{rn-sn} \tag{5.5}$$

Hence, $T_c = T_{sn-rn}$ (5.6)

$T_a = T_{rn\text{-}sn}$ (5.7)

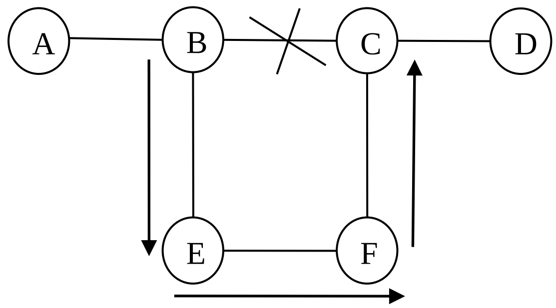
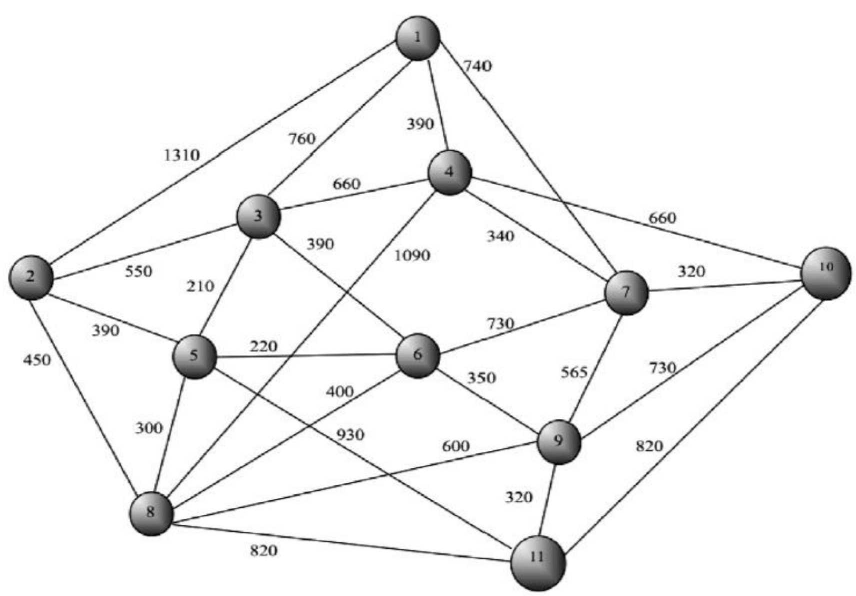


Figure 5.1 Failure link B-C and alternate backup route B-E-F-C assignment.

Here, we consider six nodes in Figure 5.1 A-B-C-D be the primary route, if link B-C fails then the backup route is provided through B-E-F-C. For the backup route, the FS is reserved in advance. The recovery setup message is generated at the link source node immediately after the detection of the failure of the link at the link source node to the receiving link node.



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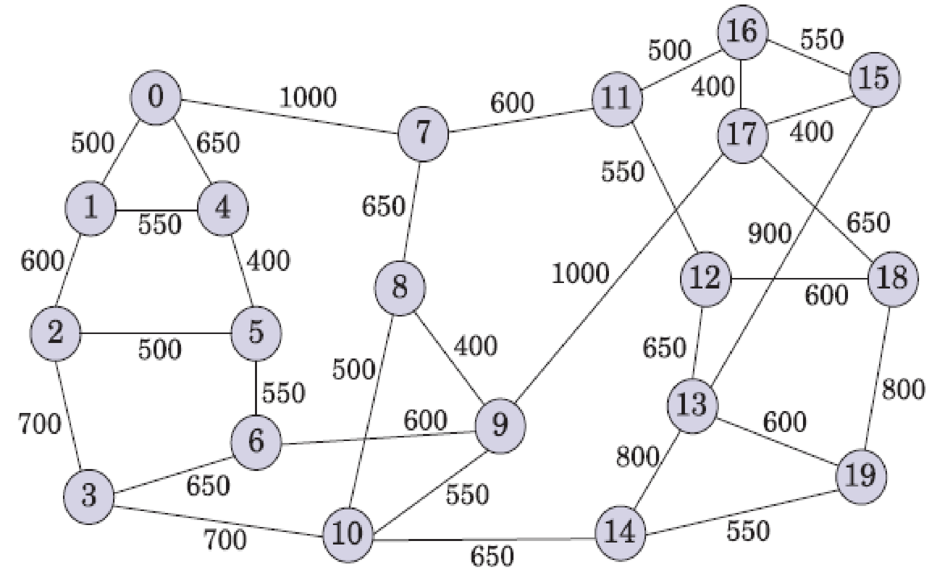

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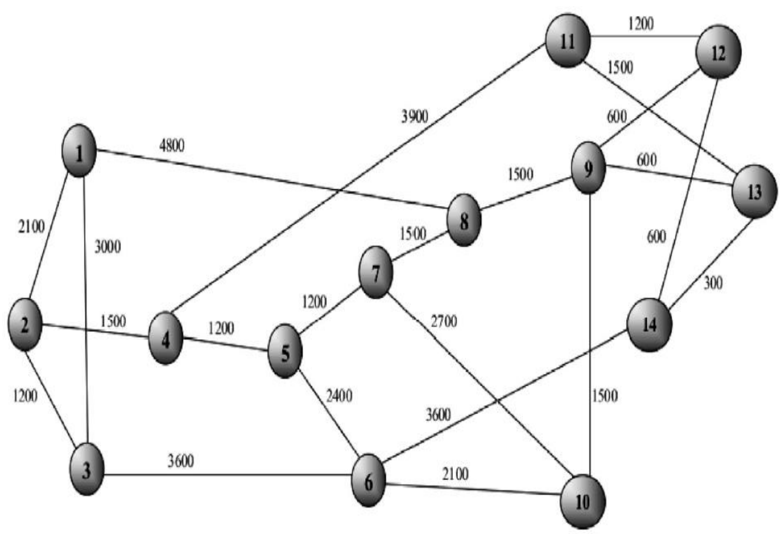


(c)

Figure 5.2 (a) COST 239 (11Nodes, 26 Links) (b) ARPANET (20 node, 32 links) (c) NSFNET (14 Nodes, 22 links).

Algorithm 5.1 for proposed link protection (PLP) scheme

For primary route

Connection request accepted $\leftarrow$ 0
For $i \leftarrow 1$ to r do
Search for the primary route $P^{i}_{s,d}$ for R_i from S_P
If $P^{i}_{s,d}$ is available then
Bandwidth accepted $\leftarrow$ Bandwidth accepted + f_i
Allocate FS to the primary route
Connection request accepted $\leftarrow$ Connection request accepted + 1

For backup route

Bandwidth failed $\leftarrow$ 0,
for i 1 to $\leftarrow$ L do
rfR^{i} number of connection request failed, when i^{th} link is considered
For $j \leftarrow rfR^{i}$ do
Bandwidth failed $\leftarrow$ bandwidth failed $+f_j$
Search for backup route $B^{j}_{sn,rn}$ for r_j from S_B
if $B^{j}_{sn,rn}$ is available then
Bandwidth recovered $\leftarrow$ Bandwidth recovered $+f_j$
end if
end for
end for

5.3 Simulated Network Parameters

Here, we consider three different topologies as given in Fig. 5.2 (a), (b), and in (c) that is COST 239, ARPANET, and NSFNET and evaluate the performance of different network parameters in MATLAB 2015 on i5, 7400 intel core processor with 3GB system and 8 GB RAM by randomly generated source and destination demands/request.

Table 5.1 The mean values of network parameters for different Schemes.

Network Parameters	**COST239**			**NSFNET**			**ARPANET**		
	DLP	**SLP**	**PLP**	**DLP**	**SLP**	**PLP**	**DLP**	**SLP**	**PLP**
Recovery Time (µs)	5.00	6.11	5.82	0.65	0.85	0.85	1.24	2.78	1.82
BBP	0.18	0.10	0.10	0.49	0.31	0.31	0.56	0.18	0.18
NCU	24.9	26.1	26.1	26.4	33.7	33.7	68.6	61.5	61.5

5.3.1 Bandwidth Blocking Probability (BBP)

The BBP is the number of bandwidth demands rejected to the total bandwidth demanded [88]. It has been noticed from Figure 5.3(a), (b), and (c) the BBP of our proposed strategy is very less as compared to the SLP. Hence, in our PLP scheme the large number of source-destination requests accepted as compared to SLP. The mean BBP for our proposed strategy DLP, SLP and PLP are 0.18, 0.1078, and 0.1078 respectively for COST239 are 0.56, 0.18, and 0.18 for ARPANET and for NSFNET are 0.49, 0.31, and 0.31 for DLP, SLP and for PLP respectively. The rejections of the connection request in DLP and SLP are more than our PLP scheme. The mean values for different parameters are provided above in Table 5.1.

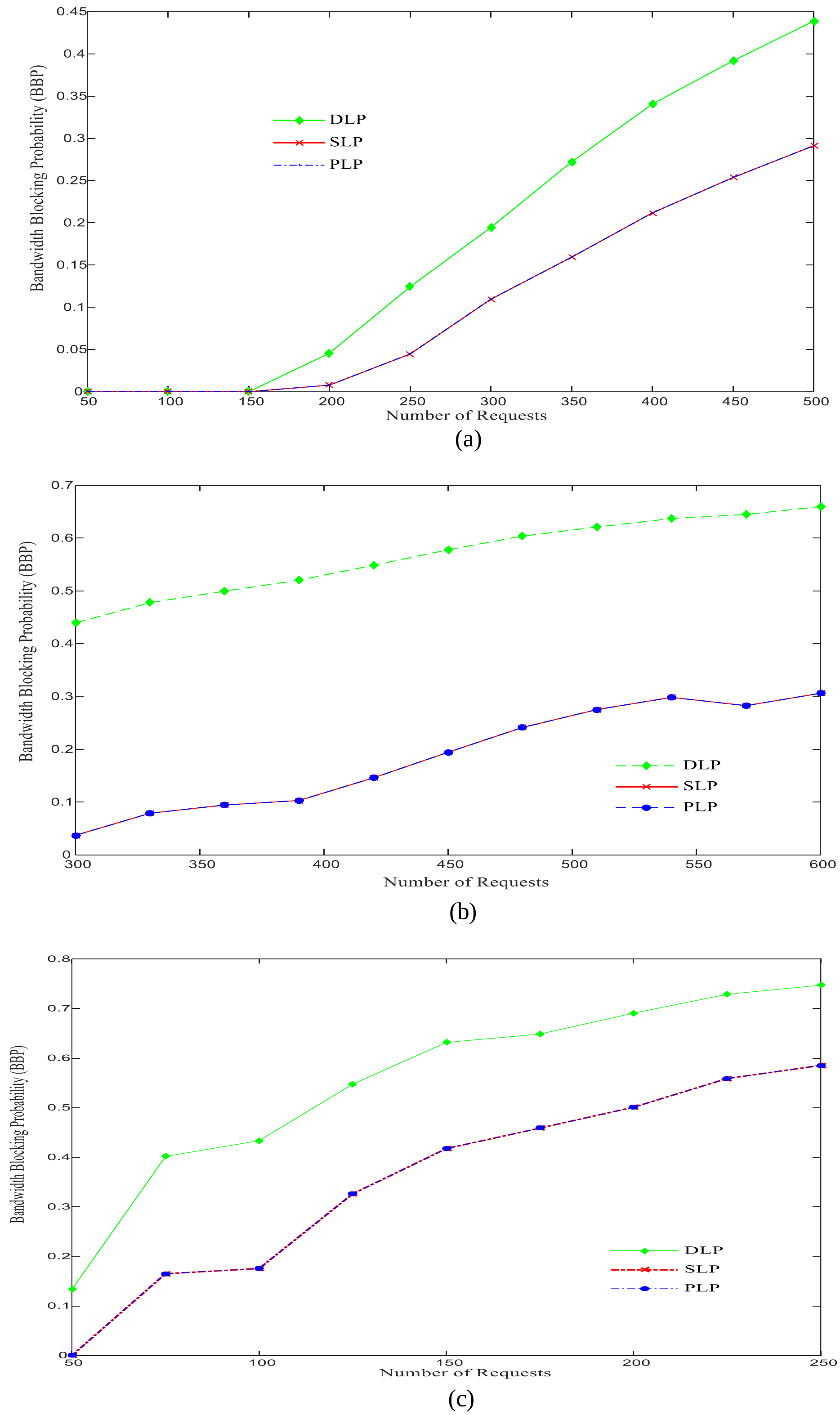
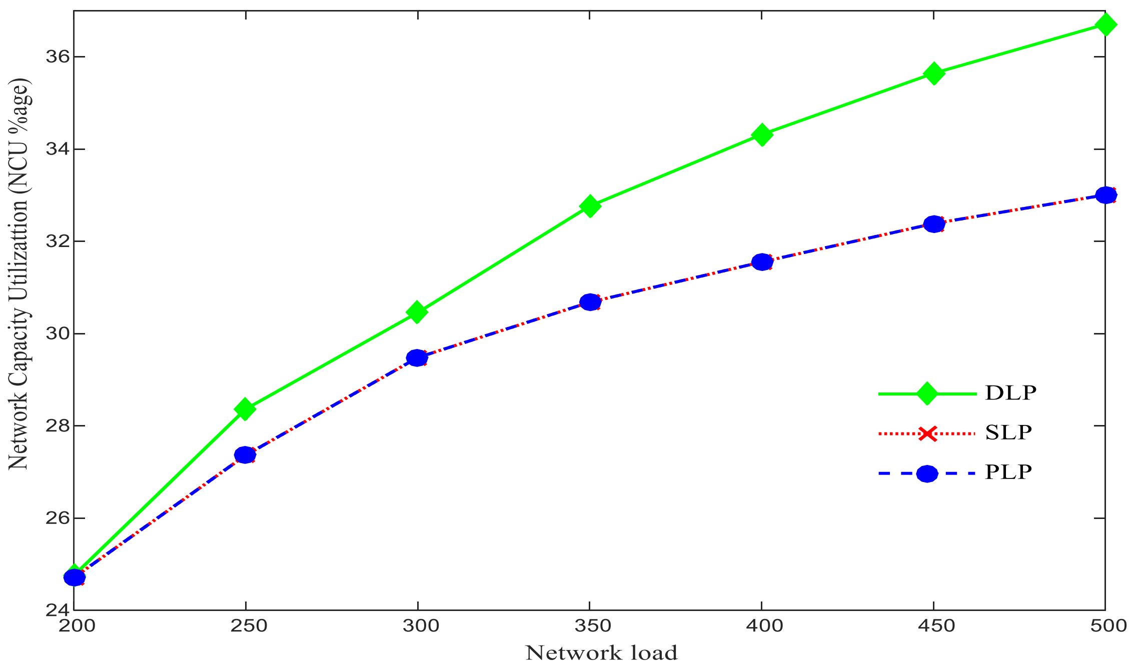


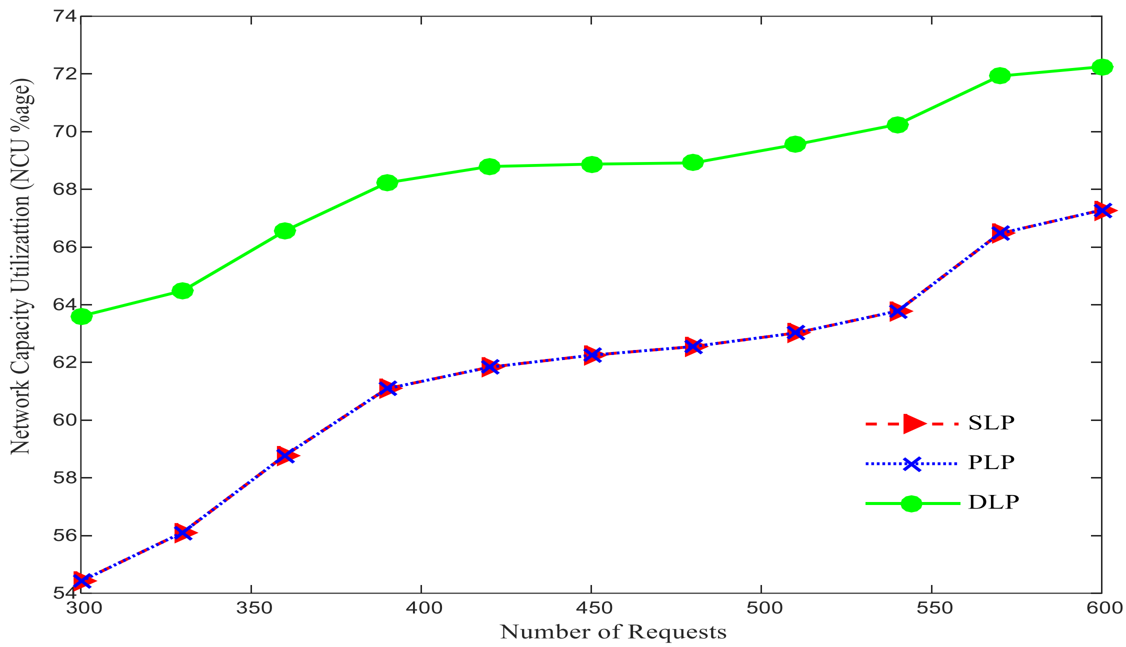
Figure 5.3 (a) Bandwidth Blocking Probability (BBP), vs. no. of requests for COST 239 and (b) BBP vs. no. of requests for ARPANET (c) BBP, vs. no. of requests, for NSFNET.

5.3.2 Network Capacity Utilization (NCU)

The network capacity utilization is defined as the total spectrum used over the total connection request accepted in the optical network. The average, of NCU for COST 239 is 24% 26%, and 26% for DLP, SLP, and for PLP as given in Figure 5.4 (a) and (b) &(c). The average NCU for ARPANET is 68%, 61%, and 61% for DLP, SLP, and PLP respectively, and for NSFNET are 26%, 33%, and 33% for DLP, SLP, and for PLP. If NCU [109] is more than 70% then slowdown will occur in-network traffic, if this remains for a long time then a long queue of traffic will occur in the optical network, which causes a stoppage in the traffic. In COST239 the traffic is less as compared to ARPANET and NSFNET. Hence traffic in COST239 is less as compared to other topologies.



(a)



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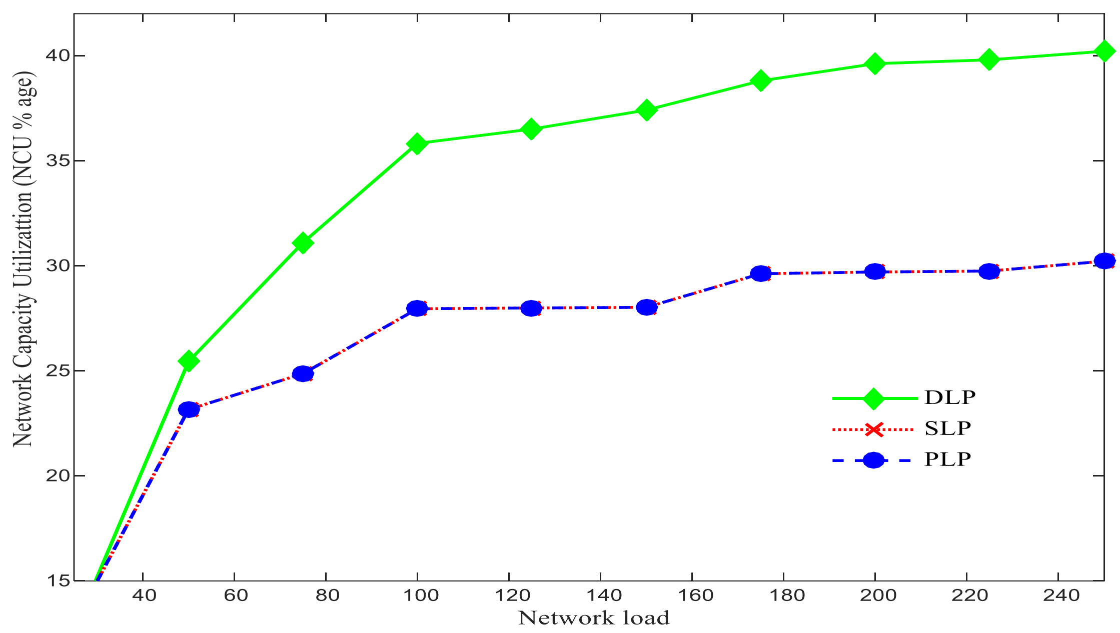
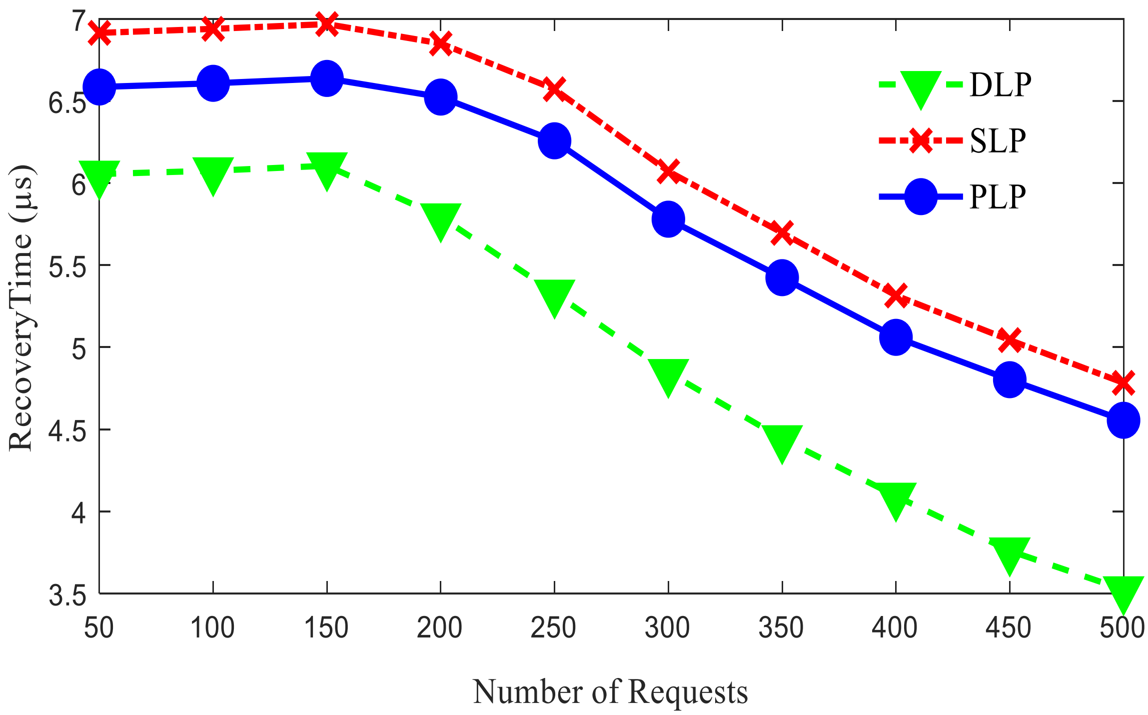


(c)

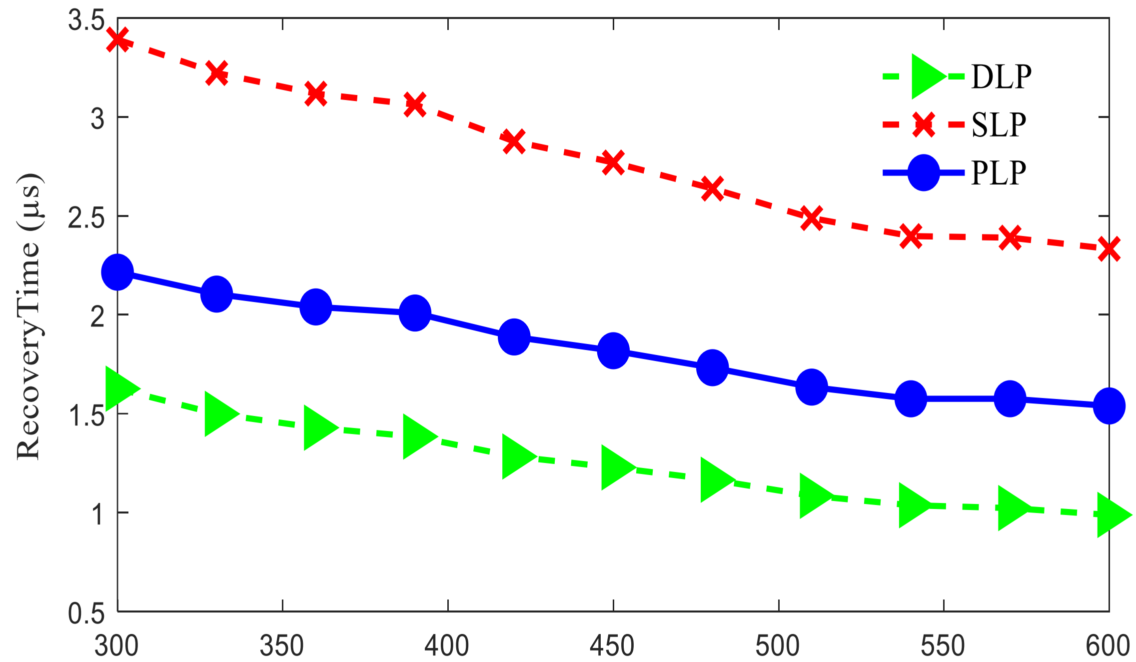
Figure 5.4 (a) Network Capacity Utilization (NCU), vs. no. of requests for COST 239 and (b) NCU vs. no. of requests for ARPANET (c) NCU vs. no. of requests for NSFNET.

5.3.3 Recovery Time

It is the time from where the recovery process is started and the confirmation message received from the receiving end to the source. For fast recovery, a recovery time constraint is required to introduce. The Recovery time mentioned in figure 5 (a), (b), and (c) for all three topologies that is Cost239, ARPANET, and for NSFNET in our PLP scheme is less than SLP and above than DLP as shown in Figure 5.5 (a) for COST239 (b) for ARPANET and (c) for NSFNET. The average of RT for DLP, SLP, and PLP for COST239 are 5.00, 6.11, and 5.82, and for ARPANET are 1.24, 2.78, and 1.82, and for NSFNET are 0.65, 0.85, and 0.85 for DLP, SLP, and for PLP respectively.



(a)



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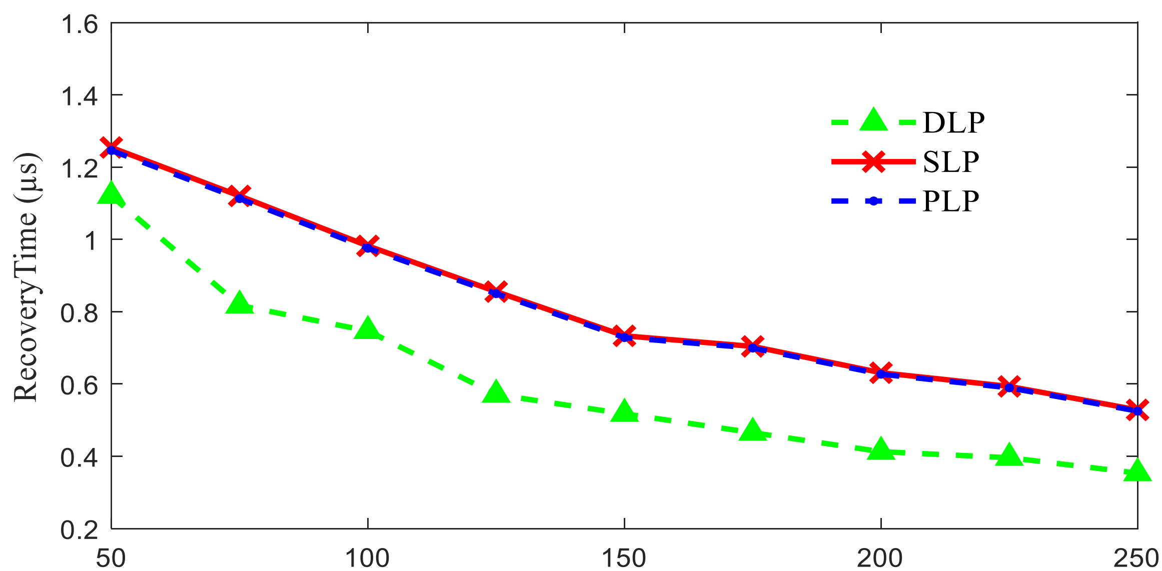


(c)

Figure 5.5 (a) Recovery Time in microsecond vs. Number of Requests for COST 239 and (b) Recovery Time vs. Number of requests for ARPANET (c) Recovery Time vs. Number of requests for NSFNET.

5.4 Summary

In the chapter, a backup link protection scheme for the recovery of failure in EON is presented. Our proposed scheme shows the recovery time between SLP and DLP. The simulation is performed for various network parameters like BBP, NCU, and recovery time for three topologies that is COST239, ARPANET, and for NSFNET. The purposed PLP strategy shows the optimized performance when compared to other strategies.

CHAPTER 6

DUAL LINK FAILURE SURVIVABILITY WITH RECOVERY TIME CONSTRAINT

This chapter addressed a fast connection recovery scheme for a double link failure in elastic optical networks (EON). The EON has the capability to meet the next generation (5G) or higher bandwidth requirement. The survivability of a high-speed optical network is very essential. As the network size increases, the traffic in the network also increases, which resulting in the probability of multiple failures, and component failure at the node also increases. Here, we proposed a parallel cross-connection backup survivable strategy for a dual-link failure in the optical network. Our proposed scheme has minimum bandwidth blocking probability (BBP), lower bandwidth provisioning ratio, and fast connection recovery time, as compared to the existing dedicated path protection (DPP), and shared path protection (SPP) schemes. Simulation is performed for ARPANET and COST239 topologies.

6.1 Introduction

As reported by Cisco [24], a threefold increase in global traffic in the next five years up to 2022. Internet traffic grows rapidly globally at an annual rate of 27% from 2017 to 2022. Cisco forecasted the monthly mobile data rate by 2022 will be 77 exabytes and annually it will be one zettabyte [24] [110] and mobile occupied about 20% of the internet traffic by 2022. The bandwidth of optical fiber is very high, for next-generation evaluation, it requires an extension in existing fixed grid dense wavelength division multiplexing (DWDM) network of 50 GHz or 100 GHz homogenous and fixed modulation format will not be able to cope with variable bandwidth demand [99], at low bit rate, which causes wastage of spectrum. Higher bit rate (400gb/s or 1Tb/s) demands are not met by the existing fixed DWDM scheme [111].

The Elastic optical network (EON) with bandwidth and transponder flexibility has been viewed as a spectrum efficient solution for higher bandwidth demand applications [113] [114]. The existing homogeneous optical network needs to replace the opaque architecture with the latest transparent network which has energy-efficient and considerable cost equipment [112].

The bandwidth demand increases continuously due to the continuous growth in internet traffic [24] such as social networks, cloud computing, multicasting, broadcasting, high definition video streaming (HDVS), and online gaming, etc. All these applications required higher bandwidth for next-generation high-speed optical networks. EON replace the fixed channel DWDM with finer frequency slot (FS) channel width 6.25 GHz, 12.50 GHz, 25 GHz or 50 GHz [27]. Bandwidth variable transponder (BVT) ranging from 10 Gbps to 200 Gbps [115]. The requested bandwidth by the users is integer multiple of these FS. Despite EON, the capacity of the fiber is limited by Shannon capacity limitation, the nonlinear spectral channel interaction is a more important factor that limits the capacity of the optical fiber [116].

As the size of the optical network increases, correspondingly the probability of the single, and double link failure is also increased. In EON, the link failure causes vast data loss and a huge disruption to the customer's businesses and provides a poor quality of services (QoS) to the users. The failure in the network not only affects the quality of services but resulting a huge revenue loss to the network operator [44] and also causes huge congestion in the network.

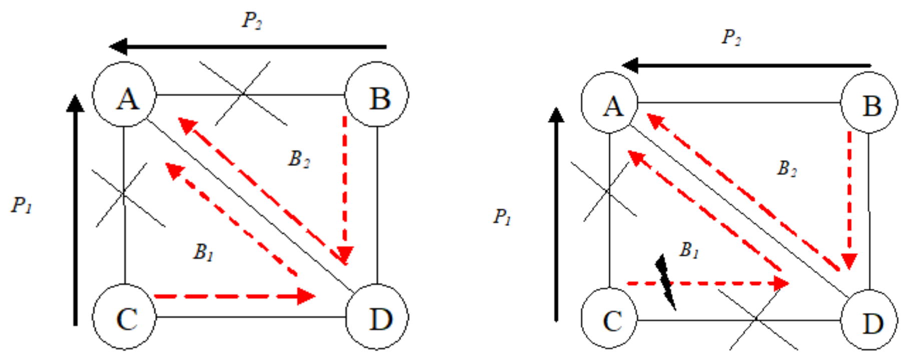
Network survivability is the main issue in the EON. There are two main survivability schemes one is protection and the other is restoration. In an earlier scheme, the backup route is reserved in advance at the time of connection establishment and ensures to provide guaranteed 100% protection against any primary link failure in the optical network. The reserved FS not used until the failure happened in the network. In a later scheme, the backup path is searched dynamically after the failure occurred in the network but not provided the guaranteed recovery of the network. The survivability issue in EON becomes more compelling due to spectrum continuity and contiguity constraint [88] [117]. The spectrum continuity constraint requires the same number of FS on each link, whereas the contiguity constraint follow the successive FS on each light path [59]. In EON, both the working and protection paths have to gratify the spectrum continuity and contiguity constraints. These spectrum constraints cause more complexity while designing the EON as compared to the fixed DWDM network. This paper presents a survivable scheme, for dual-link failure [118] in EON [119]. Here, we consider that the two links are failing arbitrarily [31] and the recovery path provided links disjoint and established at the time of connection setup.

6.2 Related Work

In EON, the flexible sliced spectrum assignment is used for each request rather than the fixed spectrum assignment in DWDM [56]. Most of the previous work provides a survivability scheme for single link failure in EON. For EON different RSA model has been developed with or without considering the level of modulation [120][23]. The spectrum continuity and contiguity constraint are also considered for RSA in EON [121] [122]. The spectrally efficient and spatial flexible network is proposed in [123]. The survivability of link and equipment failure at the node is a more critical issue in the optical network. Several network design has been proposed for the management of the spectrum in EON [61], dual-link failure [124], restoration [66], multipath protection [28], p-cycle design [41], mapping of virtual network design [86], multicast survivability [71] all are presented in the literature with an objective of proficient utilization of the resources. The first and last fit recovery strategy has been proposed in [76]. The comparison between dedicated path protection (DPP) and shared backup path protection (SBPP) and ILP are addressed in [59][77]. The proposed SPP in [61] and fragmentation of the spectrum [121], and the shared backup route are presented in [11]. The comparison of DPP with three strategies: 1) supporting graph-based RSA, 2) first fit FS assignment, 3) and the routing path length is presented in [77]. The minimum free spectrum block consumption algorithm (MFSB) is presented in [63]. The failure probability aware algorithm, using integer linear programming is discussed in [78]. The aware differentiated protection (ADP) algorithm agreement between the network operator and end users is explained in [64]. The performance of ADP, DPP and SPP is evaluated through open flow based software, the performance of ADP is better as compared to DPP, and SPP. The shared path protection with correlated risk (SPPCR) is presented in [65]. The spectrum utilization and energy issue for fixed and flexible grid are addressed in [125]. Hybrid adaptive frequency assignment, (HAFA) and Tabu search (TS) for SPP and DPP is presented in [80]. After failure repair optimization (AFRO) scheme is addressed in [96]. Multilink failure survivability with dynamic load balancing is addressed in [74]. The different route selection polices for fixed path (FP) and online path computation (OPC) is presented in [68]. In [97] the multipath survivability with band width clutching for EON is provided. The single path provisioning, with bitrate are presented in [67]. The higher resource sharing with multipath protection is explained in [28]. The survivable virtual optical networking which is also known as optimum shared protection mapping (OSPM) is provided in [86].

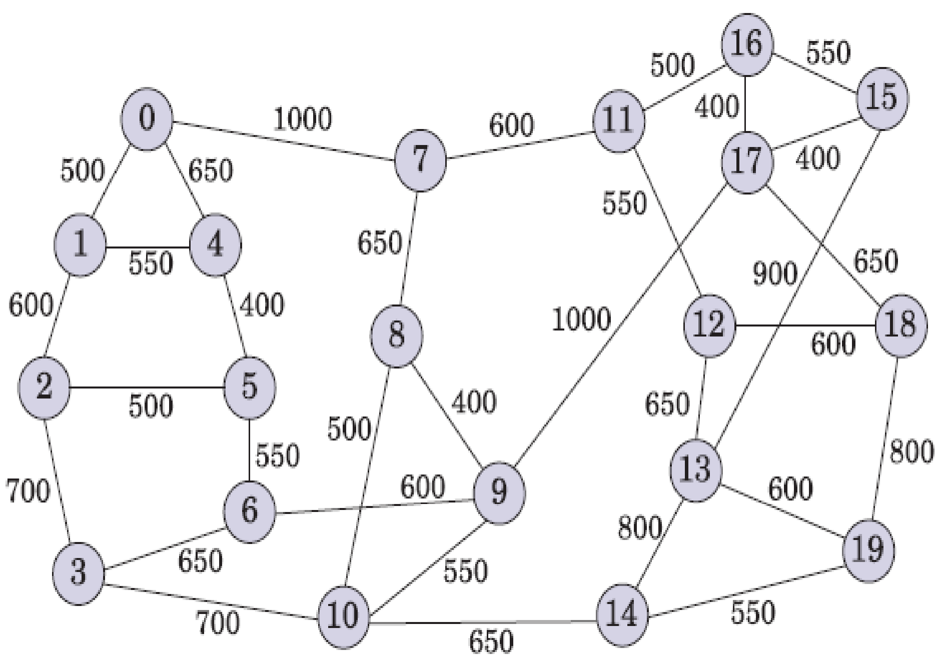
6.3 Dual-link failure

In this Section, two cases for dual-link failure are presented. In the first case, different links with different primary routes fail simultaneously. And, in the second case, links of primary and backup routes fail simultaneously. In Figure 6.1 (a) we consider the first failure on the primary route, P_1 (C-A), and simultaneously the second failure P_2 (B-A) occurred on primary route P_2. The backup of both these routes are B_1 (C-D-A) and B_2 (B-D-A) for P_1 and $P_{2,}$ respectively, which shared the same FS. Similarly in Figure 6.1 (b) the failure occurred on the primary route, P_1 (C-A), and simultaneously the backup route, B_1 of P_1 also fail, for which the backup route B_2 (B-D-A) is provided. For the backup links, we required additional spare capacity in the network and used it only when it's necessary. In our proposed INCB-SPP, the primary backup route (PBR) always exists.

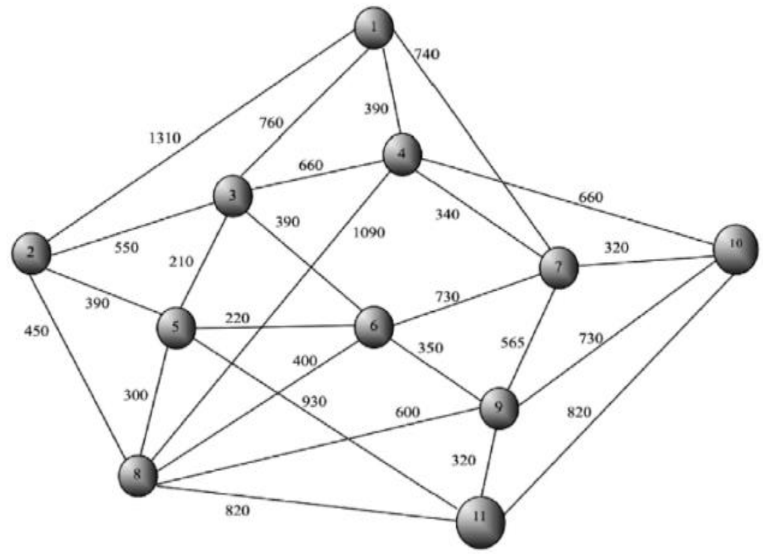


(a) (b)

Figure 6.1 (a) For Primary (P_1) = C-A, B_1 (Backup) =C-D-A and For Primary, (P_2) = B-A, B_2 (Backup) = B-D-A (b) For P_1= C-A, B_1 = C-D-A and for P_2 = B-A, B_2 =B-D-A.



(a)



(b)

Figure 6.2 (a) ARPANET topology with 20 nodes and 32 links, (b) COST 239 topology with 11 nodes and 26 links.

6.4 Notations Used

G (V, L, F): Consider a network topology with $|V|$ nodes and $|L|$ links. Each link $l \in L$ and have its beginning node *s(l)* and receiving node *r(l)*.

v	Nodes in the network topology, ($v_1, v_2, v_3, \ldots . v_n$ be the set of the nodes in the network) $v \in V$
l	Links in the network topology, ($l_1, l_2, l_3, \ldots \ldots l_n$ be the set of links in the network) $l \in L$
f	Set of FS on each link, ($f_1, f_2, f_3, \ldots \ldots . f_n$) indexes as $f \in F$.
d	Set of traffic request, each request has its origin at *s(d)* and *r(d)* is the receiving end $d \in D$
w	Working / primary path in the network $w \in W$
r_b	Reserved backup path in the network $r_b \in R_b$
ℓ^f	f^{th} frequency slot on link ℓ
ℓ_w^f	f^{th} frequency slot of w^{th} working route on link ℓ
$l_{r_b}^f$	f^{th} frequency slot of ${r_b}^{th}$ backup route on link ℓ
RT_r	Recovery time of request r, $\forall r \in R$
R_{tc}	Recovery time constraint

The evolution of different network parameters is as follows:

- Failure detection time is the time taken by the node to detect the failure, we consider the failure detection time, f_d is 10µs [59].
- Message processing (M_p) time at the node is 10µs.
- Delay in signal propagation, (s_{pd}) on each link is 400µs for every 85km.
- Cross-connection is the connection establishment time (c_x), we consider the cross-connection time is 2ms.
- The number of links (b_l) in the backup light path.
- p_t be the propagation time of the message.
- n, be the Number of nodes and M_a be the message acknowledgment time from destination to source and l be the length of the backup light path.

6.5 Network constraint

Different network constraints have been considered while designing the survivable network.

6.5.1 Maximum capacity of the link

The number of FS is equal to or less than the number of FS available on that link.

$$\sum_{\forall f \in F} l^f, \qquad \forall l \in L \tag{6.1}$$

6.5.2 Spectrum continuity and contiguity constraint for primary and backup route

For continuity constraint, this constraint requires the same number of FS to each link

(i) For primary path

$$l^f_{w_i} - l^f_{w_k} = 0,\ \forall i \neq k, \forall f\ \varepsilon F,\ \forall w\ \varepsilon W, \forall l\ \varepsilon L \tag{6.2}$$

(ii) For backup path (Reserved path)

$$l^f_{r_{bi}} - l^f_{r_{bk}} = 0, \forall i \neq k, \forall f\ \varepsilon F, \forall r_b\ \varepsilon R_b, \forall l\ \varepsilon L \tag{6.3}$$

For contiguity constraint

In contiguity constraint, we consider the number of FS request arrives is *FR*.

(i) For primary path

$$l_w^{f_i} - l_w^{f_k} = FR - 1, \forall i \neq k, \forall f \, \varepsilon \, F, \forall w \, \varepsilon W, \forall l \, \varepsilon \, L \tag{6.4}$$

(ii) For backup path (Reserved path)

$$l_{r_b}^{f_i} - l_{r_b}^{f_k} = FR - 1, \forall i \neq k, f \, \varepsilon \, F, \forall r_b \, \varepsilon \, R_b, \forall l \, \varepsilon \, L \tag{6.5}$$

6.5.3 Recovery time constraint (RTC)

RTC is the maximum connection setup time of the network after the failure. T_{rcs} be the recovery time of the connection setup and R_{tc} is the recovery time constraint.

$$T_{rcs} \leq R_{tc} \tag{6.6}$$

6.6 Proposed and Existing Survivability Strategies

Here in this Section, we explained the existing survivability schemes i.e. SPP, and DPP, and then our proposed recovery scheme that is intermediate node cross-connects backup route for shared path protection (INCB-SPP). The different failure scenarios of failure are presented in Figure 6.1 (a) and (b).

6.6.1 Shared path protection (SPP)

In this scheme, the spare capacity is shared with other light paths. In SPP, the backup path is pre-decided; the FS is reserved in advance but not used until the failure occurred in the network. When a working link fails, the whole traffic is diverted to a reserved backup path. For recovery of a single link failure, the entire working path in the network must share the same unused capacity that is linked disjoint to each other. SPP requires less than the DPP. In SPP the cross-connection at the nodes increases the connection recovery time. The total connection recovery time for this scheme is given as

$$RT_{spp} = f_d + 2 \times n \times (M_p + M_a) + n \times c_x + 2 \times l \times p_t \tag{6.7}$$

6.6.2 Dedicated path protection (DPP)

In this scheme, the DPP is a 1+1 scheme, the intermediate node of the backup route is already cross-connect at the time of connection setup. In DPP [77] no cross-connection is used for the backup route, hence in this case the recovery time is lower than the SPP. The total connection recovery time DPP is as under

$$RT_{dpp} = f_d + 2 \times n \times (M_p + M_a) + 2 \times l \times p_t \quad (6.8)$$

6.6.3 Proposed recovery scheme

In the proposed scheme, we have decided an intermediate node where signal exchanged information by parallel reception of connection setup messages by source and destination nodes of the failed primary route. If the recovery time is less than the pre-decided time constraints, then the connection is accepted, otherwise, it is rejected.

$$RT_t = f_d + T_{cs} + T_{ack} \quad (6.9)$$

Here, we consider RT_t be the total recovery time, T_{cs} and T_{ack} are the total connection setup time and the total acknowledgment time for connection recovery.

Algorithm 6.1 for intermediate node cross-connect back up route for shared path protection (INCB-SPP)

Consider a given network G (V, L, F), with V numbers of nodes, L links, and every link with frequency slots F.

d: Number of Connection requests

D $\{s(d), r(d), f\}$: number of connection request with the source $s(d)$, destination $r(d)$, and the demand of frequency slots (f).

W_i: Working light path from source(s) to destination (d), for connection request D_i

R_{bj}: Backup light path from source node (s) to destination node (d), for connection request D_{bj}

S_P: Spectrum assignment for the primary route

S_B: Spectrum assignment for the backup route

For primary route

1: Connection request accepted $\leftarrow$ 0, Bandwidth accepted for the route
2: Connection request accepted $\leftarrow$ 0
3: For i $\leftarrow$ 1 to r do
4: Search for the primary route W^i_{s-d} for D_i from S_P
5: If $W^i_{s(d)-r(d)}$ is available then
6: Bandwidth accepted = Bandwidth accepted + f_i
7: Allocate FS to the primary route
8: Connection request accepted = Connection request accepted + 1
For backup route
9: Bandwidth recovered $\leftarrow$ 0
10: Bandwidth failed $\leftarrow$ 0, bandwidth for the route
11: for i $\leftarrow$ 1 to L do
12: fD^i number of connection request failed, when i^{th} link is considered
13: For j $\leftarrow$ fD^i do
14: Bandwidth failed = bandwidth failed +f_j
15: Search for backup route $B^j_{s(d)-r(n)}$ for d_j from S_B
16: if $B^j_{s(d)-r(n)}$ is available then
17: Bandwidth recovered = Bandwidth recovered +f_j
18: end if
19: end for
20: end for

6.7 Analysis of network parameters

In this paper, we consider three existing topologies as shown in Fig. 6.2 (a) and (b) that is ARPANET (US network) and COST239 and evaluate their performance for the backup route by randomly generated source-destination, connection demand by using *N (N-1) /2*, *N* be the number of nodes, and simulate in MATLAB 2018 on i5 with 8GB RAM, Intel core processor. The FS for heterogeneously random connections are generated for ARPANET and COST239. The three network parameter performance is evaluated for ARPANET and COST239 is as under.

Table 6.1 Average value of network parameters for the different protection schemes.

Network Parameters	**ARPANET**			**COST**		
	DPP	SPP	INCB-SPP	DPP	SPP	INCB-SPP
BBP	0.7072	0.4041	0.3828	0.3947	0.0455	0.0154
RT (μs)	8715	16338	4683	8201	12474	3799
BPR	6.0223	2.8712	2.7161	3.5045	1.7549	1.7149

6.7.1 Bandwidth blocking probability (BBP)

Bandwidth blocking probability is defined as the ratio of the total number of requests rejected to the total number of requests demanded in the network. The BBP is directly proportional to the total number of requests available in the network. When the number of arriving connection requests is lesser and the network capacity is larger than the connection request acceptance ratio is more. As the number of connection requests increases the rejection of connection requests also increases and the acceptance ratio decreases. Figure 6.3 (a) and (b) presents the BBP for all three survival strategies for ARPANET i.e. DPP, SPP, and for Intermediate node cross-connect backup for shared path protection (INCB-SPP). The BBP of our proposed scheme is very less than DPP and SPP it goes on increasing as the connection request increases. The average of BBP for ARPANET is 0.7072, 0.4041 and 0.3828 for DPP, SPP and INCB-SPP respectively and for COST239 is 0.3947, 0.0455 and 0.0154 for DPP, SPP and INCB-SPP respectively.

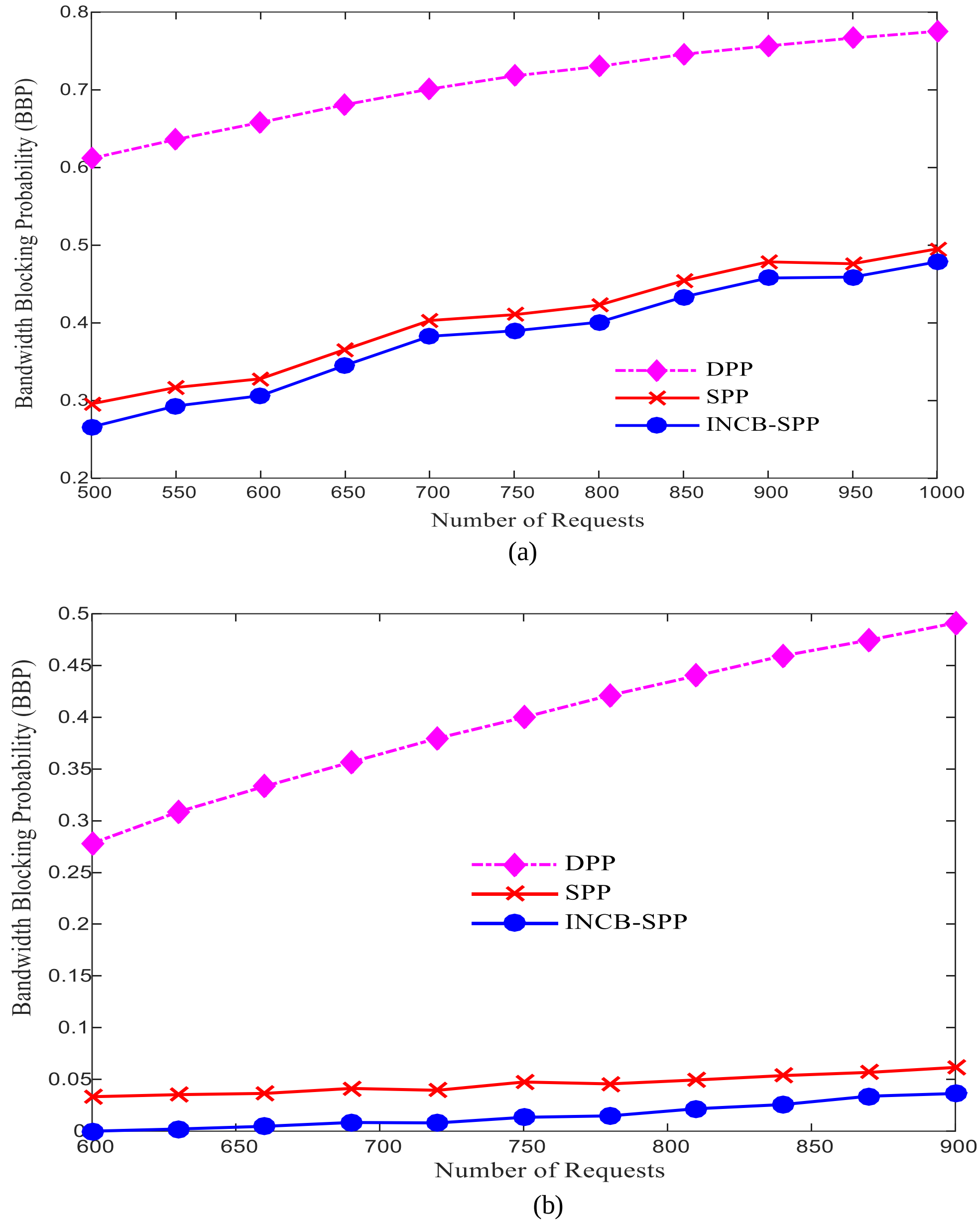
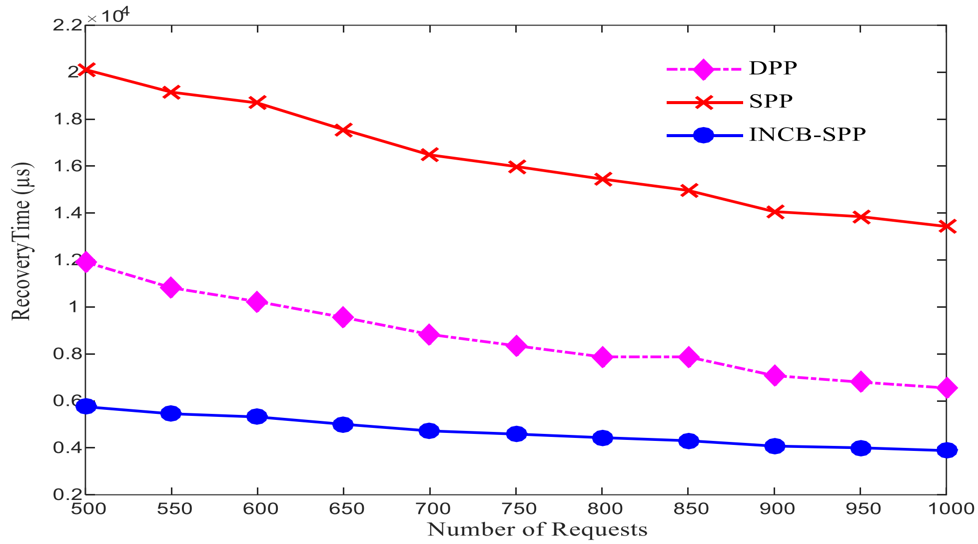


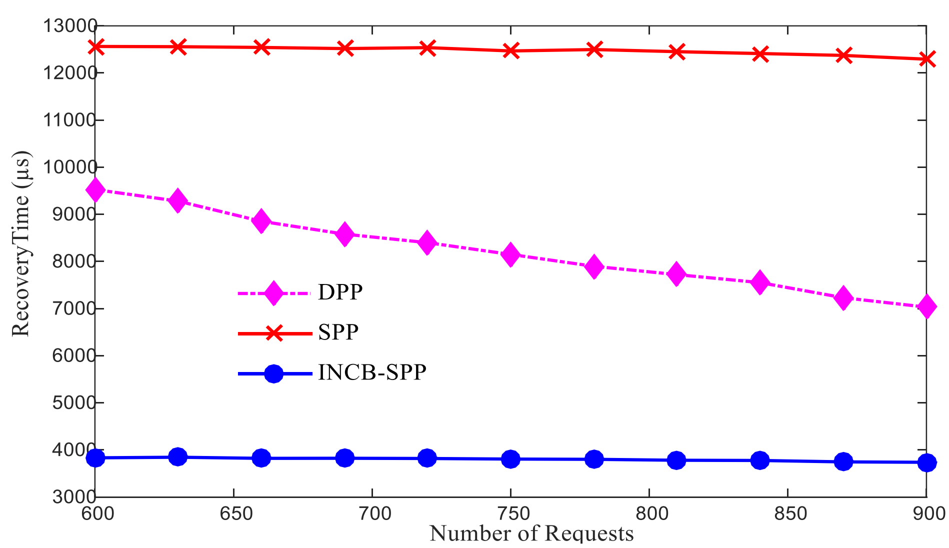
Figure 6.3 (a) Bandwidth blocking probability (BBP) vs. the number of requests for ARPANET (b) BBP vs. the number of requests for COST239.

6.7.2 Recovery time (RT)

RT is the time at which the recovery process in the network started and the connection setup message received. RT of INCB-SPP must be less than SPP and DPP as shown in Figures 6.4 (a) and (b). The recovery time constraint (RTC) has been introduced for achieving the fast recovery of the failure in the network. The RTC for ARPANET and COST239 set 45 ms and 21 ms, respectively. The RT for our INCB-SPP strategy is very less and going on decreasing as increases the number of connection requests. The simulated average, RT for ARPANET is 8715μs, 16338μs, and 4683μs for DPP, SPP and for INCB-SPP and for COST239 is 8201μs, 12474μs, and 3799μs for DPP, SPP, and INCB-SPP respectively.



(a)

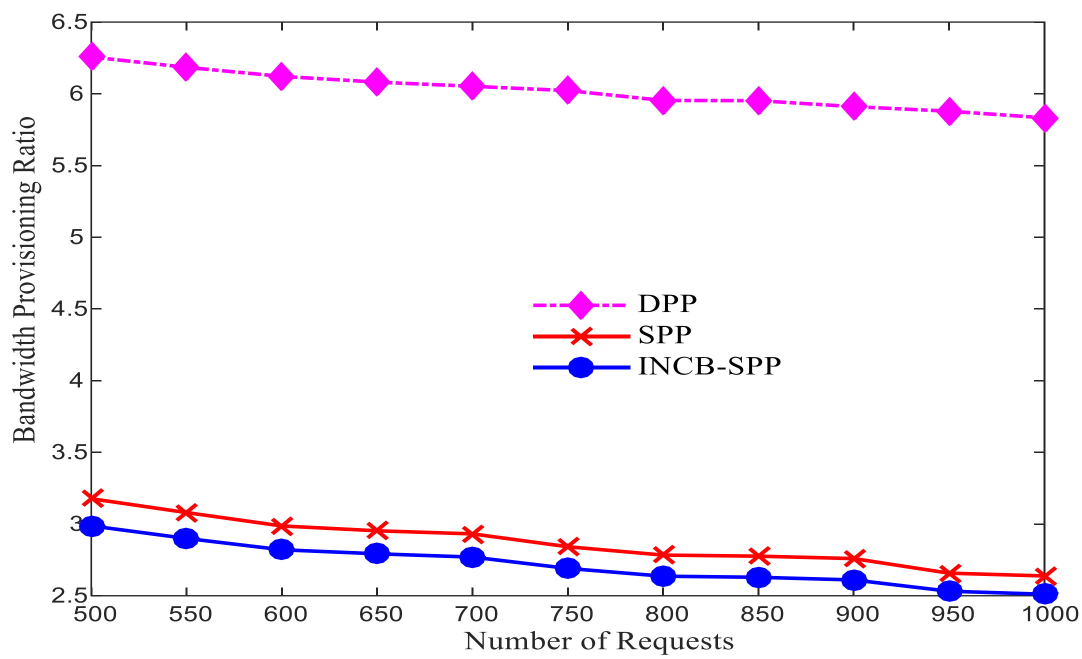


(b)

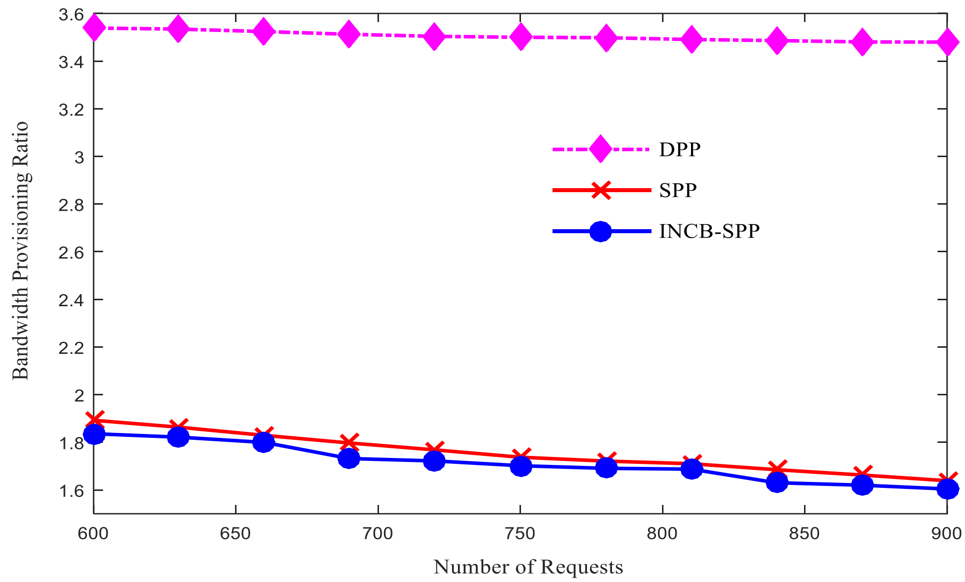
Figure 6.4 (a) Recovery time in micro second vs. no. of requests for ARPANET (b) recovery time vs. no. of request for COST239.

6.7.3 Bandwidth provisioning ratio (BPR)

BPR is the ratio of the total FS used in the network to the total FS request accepted in the network. The average value of BPR for ARPANET is 6.0223, 2.8712, and 2.7161 for DPP, SPP, and INCB-SPP, and for COST239 is 3.5045, 1.7549, and 1.7149 for DPP, SPP, and for INCB-SPP respectively. In our proposed INCB-SPP and SPP the sharing of network resources increases with the increase in the number of requests, hence, the BPR in either case for both the topologies decreases with the increase in connection request as given in Figure 6.5 (a) and (b). In the case of DPP only the shorter routes are accepted, for the longer route the sharing of resources are unavailable.



(a)



(b)

Figure 6.5 (a) Bandwidth provisioning ratio, (BPR) vs. no. of requests for ARPANET (b) BPR, vs. no. of requests for COST239.

6.8 Summary

In this chapter, we presented a realistic protection framework for a dual-link failure in EON. Despite providing a 1+1 conventional protection (DPP) and SPP, we introduced an INCB-SPP recovery scheme for a primary link failure and backup route failure in EON. The proposed scheme not only provides fast connection recovery but also utilizes network resources optimally. The maximum survivability for a dual-link failure can be achieved by providing small additional spare capacity in the optical network.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

The research work carried out in this thesis focuses on the design of the survivable optical network. We design four different survivability schemes for different types of failure in EON. For these survivability schemes, we evaluate the performance of various network parameters like BBP, NCU, BPR, RO, and RT.

7.1 Conclusion

The survivability of the optical network is investigated by using various network parameters. The various recovery strategies for a failure in the optical network are listed as follows:

- The halfway signal exchange-shared path protection scheme has been addressed for the recovery of failure in EON. This scheme provides the connection setup message from source and user end node, to the intermediate node and acknowledgment, to the respective nodes simultaneously. The HSE-SPP has better performance in terms of some network parameters like RT, BBP, BPR, and RO than SPP and DPP.
- Here, we design a path-based recovery scheme (PBRS) for arbitrary generated source–destination requests for COST239 and NSFNET. Our path-based proposed scheme shows lower BBP and NCU and the RT is also better as compared to SPP and DPP.
- The link-based recovery scheme has been designed for the survivability of a single link failure in EON. This scheme shows better recovery time as compared to SLP and DLP. The proposed link protection shows the optimal performance when compared with SLP and DLP.
- The proposed protection scheme provides a framework for a dual-link failure in EON. Despite providing a 1+1 conventional protection (DPP) and SPP, we introduced an INCB-SPP recovery scheme for a primary link failure and backup route failure in EON. The proposed strategy not only provides fast connection recovery but also utilizes network resources optimally. The maximum survivability for a dual-link failure can be achieved by providing small additional spare capacity in the optical network.

7.2 Future scope

This research provides a new direction for the survivability of the elastic optical networks. Based on the research presented in this thesis, some research that can be carried out in the future are summarized as follows:

- HSE-SPP can be applied in designing other survivable problems such as multicore optical networks, and for dual-link failure.
- In the future, we can purpose a PBRS for the selection of a safer light path and the protection strategy for the multiple failures in the network.
- The proposed PLP scheme can be applied for multiple failures in the EON.
- In the future, an INCB-SPP scheme can be applied for multiple backup failures in the optical networks and for the survivability of multiple sensor networks.

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APPENDIX 1

Network parameters used for the analysis of survivability of the optical network

Description	Parameters Value
• Failure detection time	10µs
• Message processing (M_p) time at the node	10µs.
• Signal propagation delay (s_{pd}) on each link	400µs for each 80km.
• Cross connection	10ns,10ms, 2ms, 500s

List of publications

Journals

1) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Proactive Connection Recovery Strategy with Recovery Time Constraint for Survivable Elastic Optical Networks," ***IEEE China –Communications*** *(SCIE)*, accepted, Jan. 2021.

2) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "A Parallel cross-connection recovery scheme for dual-link failure in elastic optical networks" *Journal of Optical Communications (JOC) (SCImago-Degruter, Scopus since 1980),* accepted, Dec. 2020. DOI: 10.1515/joc-2020-0252

3) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Recovery of a single link failure in all-optical networks based on the cuckoo search algorithm," *International Journal of Intelligent Engineering Informatics (IJIEI- Inder Science,) ESCI, ACM Digital Library*, Accepted, Dec. 2020.

4) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Resource efficient recovery scheme for double link failures in elastic optical networks," *Materials Today: Proceedings Elsevier Scopus,* Oct. 2020, Accepted. DOI: 10.1016/j.matpr.2020.10.915

5) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Path-based recovery scheme for a failure in elastic optical networks," *International Journal on Emerging Technologies (IJET), Elsevier Scopus Indexed*, vol.11, issue 4, June 2020, pp. 178-183.

6) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Proactive fast connection recovery scheme for a failure in elastic optical networks," *International Journal on Emerging Technologies (IJET), Elsevier Scopus Indexed*, vol.11, issue 2, April 2020, pp. 1066-1070.

7) Dinesh Kumar, Ashutosh Sharma, Rajiv Kumar, Neeru Sharma, "A holistic survey on disaster and disruption in optical communication network," *Recent Advances in Electric and Electronics Engineering, ESCI, Elsevier Scopus Indexed,* 12 (6), pp.1-13, 2019. DOI:10.2174/2352096512666190215141938

Conference papers

1) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "A risk reduction approach in optical backbone networks," *IEEE International Conference on Signal Processing, Computing and Control (ISPCC-2019)*, October 10-12, 2019, JUIT, Waknaghat, India. DOI: 10.1109/ISPCC48220.2019.8988490

2) Dinesh Kumar, Ashutosh Sharma, Rajiv Kumar, Neeru Sharma, "Restoration of the network for next generation (5G) optical communication network," *Proceedings of the IEEE International Conference on Signal Processing and Communication (5th-ICSPC),* March 7-9, 2019, JIIT Noida India. DOI: 10.1109/ICSC45622.2019.8938337

3) Dinesh Kumar, Rajiv Kumar, and Neeru Sharma, "Minimizing the disconnection probabilities in optical backbone network," *Himachal Pradesh Science Congress (National Conference)*, IIT Mandi (HP) India, October 22-23, 2018.

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