Survivable Routing Mechanisms in Optical WDM Networks

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DINESH KUMAR TYAGI
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Under the Supervision of

Prof. V. K. CHAUBEY

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE
PILANI – 333 031 (RAJASTHAN) INDIA

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BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE
PILANI - 333 031 (RAJASTHAN) INDIA

CERTIFICATE

This is to certify that the thesis entitled **"Survivable Routing Mechanisms in Optical WDM Networks"** submitted by DINESH KUMAR TYAGI, ID.No. 2004PHXF0434P for award of Ph.D. Degree of the institute embodies original work done by him under my supervision.

Signature in full of the Supervisor ______________

Name : **Prof. V.K. CHAUBEY**

Designation : **Professor & Head of Department**
Electrical & Electronics Engineering Department
BITS-Pilani, Pilani Campus

Date : ______________

Dedicated

to God

for blessing me with the

best Parents, Teachers & Friends

one can have ...

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Abstract

The recent advancements in Wavelength Division Multiplexed (WDM) optical networks enable the telecommunication and data networks to operate at extremely high data rates at a relatively lower cost per bit. Such modern all optical networks provide tremendous bandwidth with a lower latency and better Quality of Service (QoS). The wavelength routed WDM network carries many light carriers of different wavelength, routed through a network switching fabric under suitable control algorithms to meet the required flexibility and reliability. Such wavelength-routed networks have emerged as a technology of choice to meet the growing bandwidth demand of real time high-speed networks. These high speed backbone transport networks are generally prone to component or links failure which causes a huge information loss. Therefore, a robust survivable WDM mesh network becomes an essential requirement for the acceptable reliability. Survivability in these networks further needs quick restorability of lighpaths through proper provisioning during the link or component failure.

Survivable routing for network survivability, thus becomes an area of importance in the field of network design, development and research. Interrupted failed traffic may be restored through survivable routing under wavelength continuity constraint, which requires a proper provisioning of resources. In WDM optical networks it can be achieved by setting up link disjoint primary and backup lightpaths for the connection requests. Hence, the problem of survivable routing and wavelength assignment is critically important to enhance the network performance. The key challenges for survivable optical networks are to devise routing mechanisms which can determine lightpaths intelligently to yield the best network throughput at minimum resource consumption. Overall networks blocking performance, throughput and restoration capability is influenced by the way information and network parameters are to be utilized to take the routing decision. Thus, sustained advancements in optical networking technology needs a thorough understanding of related subsystems and operational methodologies required to model, design, analyze and simulate the existing WDM networks. This thesis attempts to develop appropriate intelligent survivable protection and restoration routing schemes and algorithm to optimize the network performance parameters at the network control plane.

In this thesis work, Chapter 2 proposes a hybrid network survivable mechanism to establish the lightpath routing for the network survivability in the wavelength routed WDM networks. The adopted strategy is an integrated approach, which utilizes the multitudinous strength and benefit of traditional protection, and dynamic restoration approach to improve the capacity benefits, blocking probability and restoration efficiency under dynamic traffic in WDM networks. In this process it identifies a primary working lightpath and also a set of possible minimum proactive backup protection paths to handle a failure situation. When a link fault occurs, sufficient restoration bandwidth is allocated dynamically to one of these readily available pre-provisioned backup paths, to restore the disrupted lightpath traffic. The simulation study over some of the standard network topology reveals that the proposed integrated hybrid scheme provides a significant improvement in terms of blocking probability, network resource utilization and restoration efficiency when compared with the conventional proactive and reactive restoration scheme. Thus, the proposed hybrid survivability approach provides an improvement in the network performance for only a single type of service. However, the demand of each user may not be of same nature and having dissimilar network service requirements in WDM optical networks. Thus, network service operators can provide different services to satisfy the requirement of users and try to earn profit from the network. We have also considered the different categories of traffic services and proposed a scheme to enhance the performance of fault tolerance behavior of wavelength routed WDM network in the environment of multi-nature service and traffic in the last subsection of chapter. The proposed strategy has been analyzed and simulated to evaluate the performance of multi-level hybrid traffic strategy in different combination of traffic scenarios.

The selection and utilization of primary and backup paths is a crucial decision to achieve an optimized performance of survivable routing and wavelength assignment strategy in such networks. In Chapter 3, we present three heuristic approaches of route selection for survivable RWA problem in wavelength routed WDM optical networks named as Shortest Path Pair, Shortest Longest Path Pair and Longest Shortest Path Pair. For each of the arriving incoming connection requests, these heuristic schemes consider the different path length combinations in the primary route and backup route selections. These routing heuristic strategies for survivable WDM networks has been used to describe the influence of path length on the networks performance. Performance of these routing heuristics has been extensively simulated and analyzed for different topologies at varying load and number of available wavelengths. Further, an existing Joint Path Pair (JPP) selection strategy has been applied to relate performance evaluation. The proposed strategies has also been validated and compared with the JPP strategy to establish the acceptability of SPP. These investigations on route selection did not accounting the network resources and energy parameters of the network. However, the various rapidly growing services are bandwidth thirsty nature and consume huge energy. The energy consumptions expected to grow in near future rapidly due to drastically increased Internet users and legion new services. Thus, in last subsection of the chapter a resource and energy aware scheme has also been proposed to reduce the energy saving along with improved network blocking performance in a survivable optical network. The proposed algorithm shows superior blocking and energy consumption performance with respect to other compared strategies therein.

Mostly, all of the routing and wavelength assignment algorithms solve the route selection and channel assignment problem separately. In this process, a source to destination route and continuous wavelengths may not always be determinable. In order to address this issue in Chapter 4, a survivable lighpath routing and wavelength assignment strategy using maximum flow network concepts of network graph theory has been proposed. This approach determines a wavelength and the route simultaneously for incoming lighpath connection requests. In this approach, flow network represents the wavelength resources such that the survivable routing and wavelength assignment problem for WDM networks is solved efficiently. This strategy provides all the possible wavelength continuous flow paths that maximize the number of lightpaths between a source-destination node pair of the requests. It chooses a suitable path from the available multiple link-disjoint lightpaths to transmit the data for an improved network performance.

Finally, Chapter 5 focuses on a nature inspired heuristic algorithm imitating the behaviour of swarms of Intelligent Water Drops and proposes a framework for lightpath protection in WDM network using shared backup paths. The purpose of the proposed algorithm is to maximize the number of established lightpaths of traffic under minimum resource utilization to serve the connection requests using Intelligent Water Drops algorithm. The effectiveness of proposed approach is shown through the results obtained by various extensive simulations. Simulation study on the three standard chosen network

topologies reveals that Intelligent Water Drops based survivable routing and wavelength assignment mechanism has lower call blocking probability with a promising network performance against fixed alternate routing and shortest path routing. Further the proposed algorithm has also been compared with the other nature inspired Ant Colony Optimization (ACO) and Bee Colony Optimization (BCO) based approach. The proposed algorithm is found to be a better choice in survivable routing decision.

This thesis presents few robust survivable routing and wavelength assignment algorithms for optical WDM networks based on hybrid mechanism, path length, resource and energy based heuristic and nature inspired approach to improve the network performance and survivability.

Table of Contents

CONTENTS	Page No.

Chapter -3 Survivable WDM Networks: Path Length, Recourse and Energy based Routing 60-92

CONTENTS Page No.

CONTENTS Page No.

Chapter -6 Conclusions and Future Directions 155-159

List of Figures

List of Tables and Algorithms

List of Acronyms

ABC	Artificial bee colony
ACO	Ant colony optimization
BPI	Blocking probability improvement
EDP	Edge disjoint paths
FTTH	Fiber to the home
GMPLS	Generalized multiprotocol label switching
IAC	Increased accepted calls
ILP	Integer linear programming
IWD	Intelligent water drops
LAN	Local area network
LSPP	Longest Shorted path pair
MAN	Metropolitan area network
OXCs	Optical cross connects
PSO	Partial swarm optimization
QoS	Quality of service
RAMPR	Resource aware multi-light Path routing
RWA	Routing and wavelength assignment
SLP	Shortest longest pair
SPP	Shortest path pair
SRLG	Shared risk link group
SRWA	Survivable routing and wavelength assignment
TSP	Traveling salesman problem
WAN	Wide area network
WDM	Wavelength division multiplexing
WXC	Wavelength cross connect

CHAPTER - 1

Introduction

1.1 Background

The wavelength routed Wavelength Division Multiplexing (WDM) optical network provides the solution to meet the tremendous traffic demand due to its extremely high bandwidth capability. The increasing demands of huge channel bandwidth by the end users and requirements of bandwidth intensive internet applications can only be fulfilled by employing wavelength routed WDM optical networks. The internet applications such as teleconferencing, audio/video content dissemination, remote information access, web applications, video on demand, video conferencing, online banking and other multimedia applications require huge bandwidth [Mukherjee1996].

Wavelength routed WDM networks are capable of providing huge transmission bandwidth across long distance in the form of light carrier waves claiming various advantages over electronic transmission channels. By using wavelength division multiplexing, optical fiber transmission bandwidth can be exploited by multiple wavelength channels, where each wavelength can operate as an independent communication channel working up to several Gbps data rate to provide cumulating Terabits data rate [Brackett1990]. The available optical fiber transmission systems can support more than 100 wavelength channels, which can provide tens of Terabit per second data rate over a single fiber and is used as high capacity transmission link [Ramaswami1995a]. For instance, a 10 Gbps capacity can be achieved either with one channel of that bit rate or with multiplexing of four channels at each with 2.5 Gbps or even with 16 channels at 622 Mbps to realize a WDM system [Ramaswami2002] [Mukherjee2006].

Besides huge bandwidth, optical fibers also have low signal attenuation (0.2 dB/km), extremely low bit error rates, immunity to electromagnetic interference, low signal distortion, low power requirement, zero crosstalk, and high electric resistance. Transmission characteristics of optical fiber in comparison to other popular media are shown in Table 1.1 and which are well exploited to develop backbone of high-speed data traffic transport network.

Table 1.1: Characteristics of Optical Fiber [Behrouz2006]

Type of media	Frequency Range	Typical attenuation	Typical delay	Repeater spacing
Twisted pair (with loading)	0 to 3.5 kHz	0.2 dB/km @ 1kHz	50 µs/km	2 km
Twisted pair (multi-pair cables)	0 to 1 MHz	3 dB/km @ 1kHz	5 µs/km	2 km
Coaxial cable	0 to 500 MHz	7 dB/km @ 10MHz	4 µs/km	1 to 9 km
Optical fiber	180 to 370 THz	0.2 to 0.5 dB/km	5 µs/km	40 km

The Figure 1.1 presents, transmission spectrum range of electromagnetic spectrum of frequencies used for communication purposes presenting the highest possible frequency in terms of optical channels, which proves to be a strong reason for the suitability as a media for high-speed data communication. Further, this optical transmission gets boost due to suitable wavelength multiplexing and switching capabilities at much faster speed with a good reliability. Consequently, optical networks have extensively been used as the Internet backbone of the current network infrastructure due to its many advantages over traditional copper wired and wireless networks [Mukherjee2006].

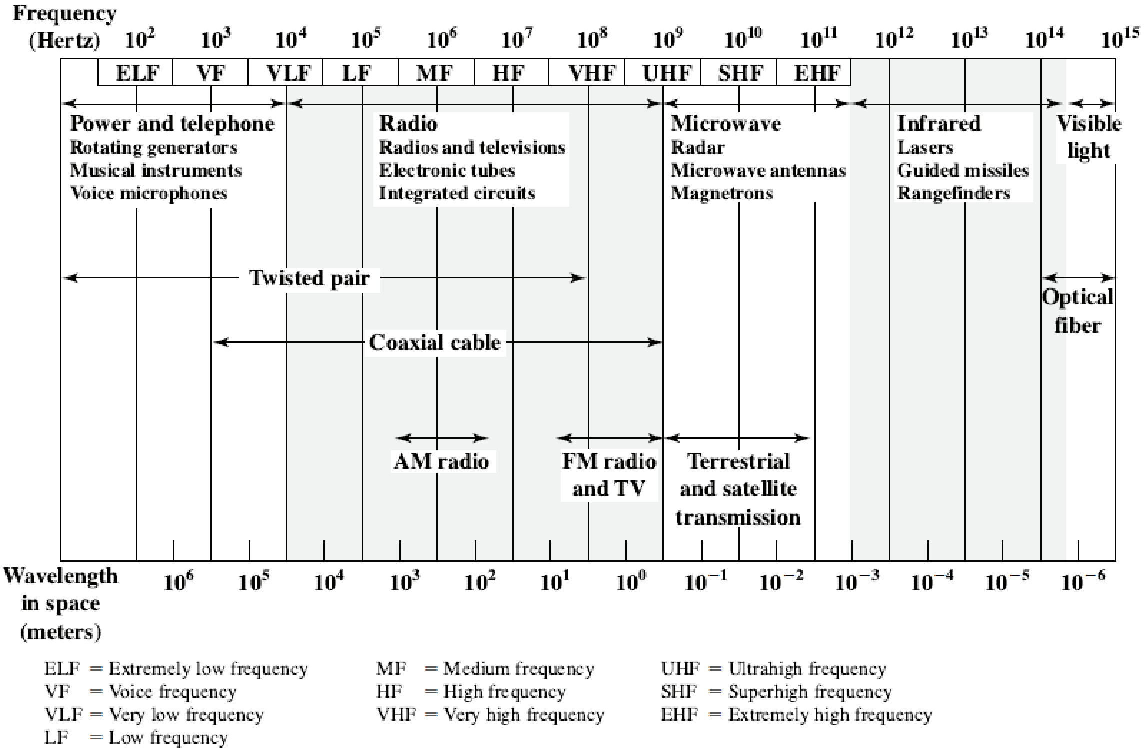


Figure 1.1: Electromagnetic Spectrum Frequencies [Behrouz2006]

The current drivers for increasing optical bandwidth includes unicast voice over IP, TDM voice, multimedia multiservice data transport that involves quality of service (QoS) enabled modern optical technology infrastructure. The QoS of optical WDM network ensure degree of transparency, level of protection, required bit error rate and various delay synchronization requirements. Such multiservice provisioning platform based networks use signaling based circuit provisioning, involving devices that perform switching in time, wavelength and space domain.

All optical networks exploit the huge bandwidth of an optical fiber to meet the ever-growing network demands of bandwidth by employing WDM technique. Backbone optical networks have also evolved to include various network topologies utilizing intelligent network elements to implement all optical control-plane to realize Generalized Multiprotocol Label Switching (GMPLS), fiber to the home or premises (FTTH), Wide Area Network (WAN) and Metropolitan Area Network (MAN) [Mukherjee2006] [Ramaswami2002].

1.2 Wavelength Division Multiplexing (WDM)

Wavelength division multiplexing is a method of transmitting data from different sources over the same fiber optic link at the same time where each data channel is carried over a unique wavelength. This technology allows the transmission of several optical signals at different carrier wavelengths on a single fiber simultaneously and the reception of the signals from the wavelength at the receiving node. The result is a link with an aggregate bandwidth that increases with the number of wavelengths employed. In this way WDM technology can maximize the use of the fiber optic infrastructure that is available. Using WDM, the tremendous optical bandwidth of a single fiber can be divided into many protocol transparent channels, each operating at an enormous speed [Mukherjee2006]. Block diagram of a WDM link is shown in Figure 1.2, which consists of transmitter, multiplexer, de-multiplexer, optical communication channel and receiver.

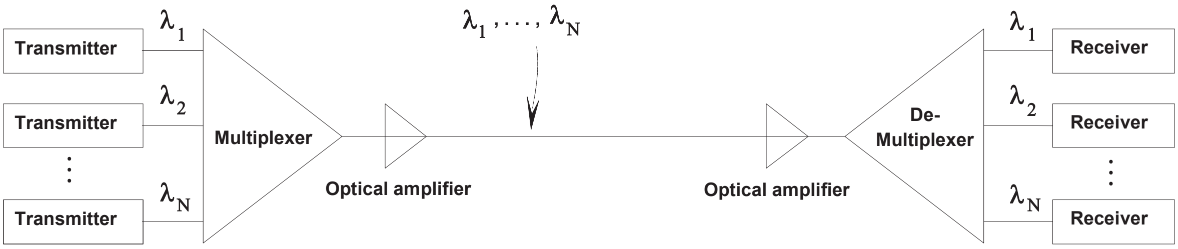


Figure 1.2: A WDM Transmission Channel

At the transmitter end, the optical information signals at different wavelengths are combined by multiplexer, which are to be transported over the single fiber. De-multiplexer separates the individual signals at different wavelengths at the receiver end.

In a fiber based WDM backbone, network end users can communicate with one another via WDM channels, which are referred as lightpaths. A lightpath may span multiple fiber links, to provide a circuit-switched interconnection between two nodes which may have a heavy traffic flow between them and which may be located far away from each other in the physical fiber network topology.

1.3 Wavelength Routed Optical Network

Recent advancements in fiber optic technology have enabled it as one of the best transmission systems for telecommunication and data networks. The wavelength routed optical networks are being deployed as backbone networks for large regions such as for nation wide network or global coverage network. In Figure 1.3 a wavelength-routed optical WDM network is shown. Access nodes will attach to the network through a wavelength sensitive routing nodes which is also known as wavelength cross connect (WXC) switch. This network consists of an optical switching fabric consisting of active switches interconnected by point to point fiber links in an arbitrary physical topology in which a WXC can switch an optical signal from an input to an output link without performing opto-electronic conversion [Banerjee1996]. Each end-user node is connected to a active WXC switch via a fiber link. The combination of an end user and its corresponding cross connect switch is called a network node. Each node is equipped with a set of transmitters and receivers, both of which may be wavelength tunable. A transmitter node sends data into the network and a receiver node receives data from the network.

Lightpath is the key mechanism of communication in a wavelength-routed optical WDM network [Ramaswami1995b]. A lightpath is an optical channel that can span multiple fiber links to provide a connection between two network nodes. As shown in Figure 1.3, the lightpath established between network nodes A and C uses wavelength λ_1, between B and F uses wavelength λ_2 and between network H and G wavelength λ_1. The lightpath between node A and C is routed via active switches 1, 6 and 7. The lightpath between node B and F is routed via active switches 6, 7, 8 and 4. End users communicate with each other via lightpaths. Thus a lightpath is a high bandwidth pipe, which is carrying data up to several gigabits to terabits per second and is uniquely identified by a physical path and a wavelength. If a node is not equipped with wavelength converters, the same wavelength must be used on all the links along the lightpath which is known as the wavelength continuity constraint.

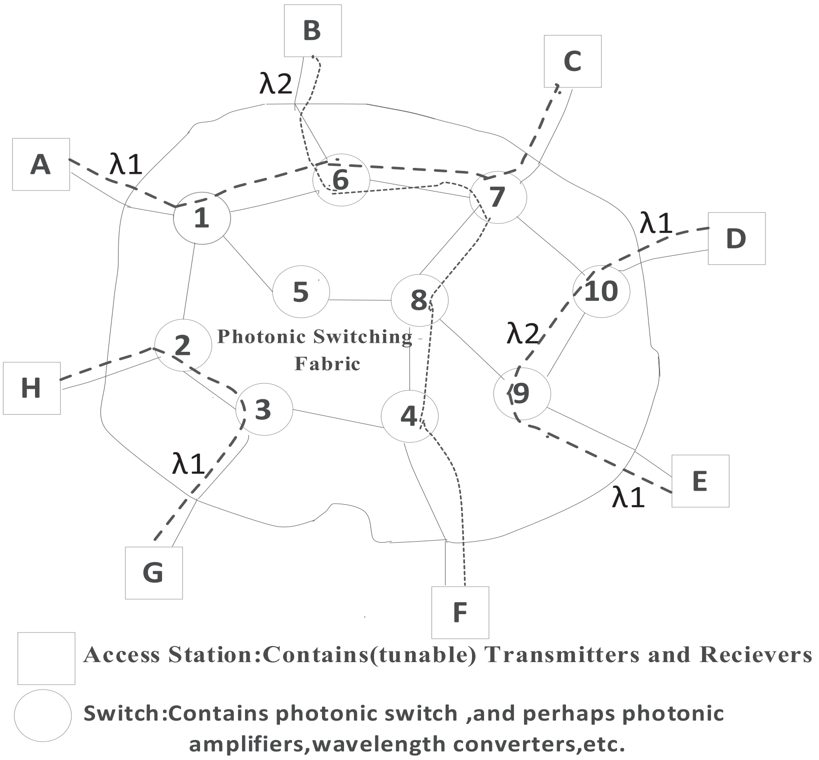


Figure 1.3: Wavelength Routed Optical WDM Network [Banerjee1996]

Due to the distinct wavelength constraints, two lightpaths cannot be assigned the same wavelength on any fiber if they do not use disjoint set of links. Using converters, different wavlength on each hop can be used to establish a lightpath. If the node is equipped with wavelength converter, it is capable of converting the wavelength of the incoming signal into another wavelength. Hence, the lightpath can use different wavelengths in the establishment of the connection path. The lightpath connection between node D and E is routed via active switches 9 and 10 which has a link with a running wavelength λ_2. Thus, to maintain the lightpath continuity node 9 and node 10 is equipped with wavelength converters due to which node 9 can convert λ_1 into λ_2 and node 10 converts λ_2 into λ_1 as shown in Figure 1.3. The blocking probability of a lightpath request is an important performance measure of a wavelength-routed network. It is affected by many factors, such as network topology, traffic load, the routing and wavelength assignment algorithm employed and whether or not the wavelength conversion is available.

1.4 Survivable Routing in WDM Networks

A lightpath is an end to end optical connection established between two subnetworks attached to optical backbone. One of the unique features of optical WDM networks is the tight coupling between routing and wavelength selection. A lightpath is realized by selecting a path of physical links between the source and destination nodes and thereafter, reserving a particular wavelength on each of the links for lightpath. Therefore, in the establishment process of optical connection, we deal with both selecting a suitable path and allocating an available wavelength for the connection. This is referred to as the routing and wavelength assignment (RWA) problem which is significantly more difficult than the routing problem in electronic networks [Banerjee1996]. Further complexity arises due to the imposed wavelength continuity constraint and distinct wavelength constraint for routing and wavelength assignment problems. Various heuristic approaches are preferred to get near optimal solutions for the better time complexity and network performance [Mukherjee2006] [Shiva2002] [Ramamurthy2002] [Zang2000]. Optical network exposed to wide range of risks due to either human activities such as link cuts, fiber cut or operational error, equipment malfunctions such as laser, optical cross connects (OXCs) failures or switching device disorder. Such failures may result in tremendous impact of revenue and data loss for infrastructure users due to high volume of traffic carrying capacity in each fibers [Ramaswami1995a]. In WDM networks two types of failure are prominent i.e. link failure and node failure. Most of the research in WDM network, focuses on recovery from a single link or node failure. Generally most modern switching devices are equipped with built in redundancy to improve their fault tolerance capability. Therefore, link failure attract more attention than node failure. Single link failure happens much more frequently than multiple link failure, thus single link failure is of more concern in networks. In addition to simply supporting logical connections between subnetworks the optical backbone must protect clients from network impairments and the failure of any resources including fiber links, nodes, lightpaths, optical transceivers and OXCs etc. to ensure reliable operation and continuity of services [James2010].

The high transmission rate of each wavelength makes survivability an indispensable requirement in WDM networks. Survivability of WDM network is the ability to reconfigure and re-establish communication upon failure of the ongoing lightpaths traffic. Since in practice not all of the links may fail at the same time, the single-link failure model is used in which at any given time at most a single link may fail. In this single link or node failure, assuming one failure is repaired before another failure is assumed to occur in the network [Ramaswami2002]. The general solution of the failure problem is able to provide a protection mechanism in the optical layer. The goal of the survivable routing and wavelength assignment (SRWA) problem is to assign a link disjoint primary and backup lightpaths to each lightpath request such that the total number of request which are accepted is maximized [Beshir2009]. The primary and backup lightpaths between E to B and G to A is shown in Figure 1.4. The primary lightpath between node E to B via node C is E-C-B and its backup lightpath via node A is E-A-B. Another primary lightpath between node G to A is via node E is G-E-A and its backup lightpath via node H is G-H-A. Backup lightpath of primary lightpath between node E and B and backup lightpath of primary lightpath of node G and A share same wavelngth λ_1 between link of node E and A.

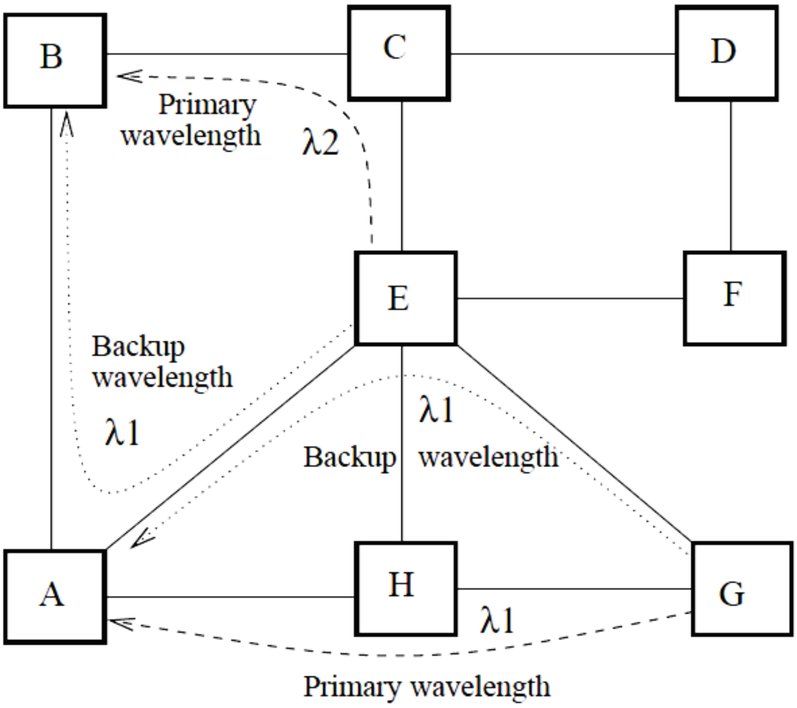


Figure 1.4: Primary and Backup Lightpaths in a Survivable Wavelength Routed Optical Network [Sen2001]

Routes for network survivability can be determined either for a connection request, which is known in advance, i.e. static SRWA or dynamic SRWA in which connection requests arrive dynamically. Dynamic SRWA is much more challenging than static case; therefore, heuristic algorithms are usually used to resolve the problem [Anand2001]. Performance of dynamic RWA algorithm is preferably measured in terms of blocking probability, which is the probability that lightpaths could not be established due to the lack of sufficient number of available resources [Ramaswami1994]. Several approaches have been suggested to get optimal solution of the problem with maximum throughput and minimum resources [Sen2001] [Ngo2006] [Mukherjee2006] [Chang2015]. In [Ngo2006] authors have applied nature inspired ant based optimization technique to optimize the routing process. [Koubia2014] addressed the problem of designing survivable optical networks through maximizing the overall network throughput by minimizing the total bandwidth consumption using resource sharing techniques of primary-backup and backup-backup multiplexing approach. To ensure that the lightpaths survive from network failures, it is important to develop a solution to SRWA problem that takes into account the requirements of lightpaths in terms of dedicated or shared protection. A diversely routed backup path (dedicated or shared) must be computed and reserved during the network design phase for each protected lightpath. The provisioning of backup lightpaths in a network will increase the capacity requirements as compared to a network that does not provide the protection [Rak2012]. Thus, the key objective in the design of survivable optical networks is to provide adequate protection with spare resource provisioning while minimizing the total network capacity.

1.5 Survivability Schemes in WDM Network

In the conventional approach of survivability in WDM network, a primary lightpath is computed and then using the shared risk link groups (SRLGs) information of primary path, an edge or node disjoint secondary lightpath is computed. Primary lightpath carries the traffic during normal operation and in case of failures of a primary lightpath, traffic is rerouted over the secondary lightpath i.e. backup path. Thus, most promising challenge in the design of optical network is survivability i.e. resilient against failure [Ramamurthy2003] [Zhou2000] [Bejerano2014] [James2010]. Survivable approach mainly includes restoration and protection mechanism as shown in Figure 1.5. Protection refers to pre-provisioned failure recovery whereas restoration refers to more dynamic recovery. The protection approach has faster recovery time than the restoration mechanism. A restoration scheme is usually resource-efficient while a protection scheme has a faster recovery time and provides guaranteed recoverability.

Protection is a proactive scheme in which spare resource reserved during the establishment of lightpath, which may be utilized to recover from lightpath failures. Dynamic restoration does not always guarantee successful recovery due to the unavailability or shortage of network resources at the time of failure recovery [Zhou2000]. However, preplanned protection always guarantees 100% resilience to failures and has faster recovery but is not efficient in resource utilization. Further, protection scheme has divided into path or link based protection. Here the former approach requires less backup resources and lower recovery delay as compared to the latter choice [Rammurthy1999b] [Ramaswami2002]. Link based methods reroute the traffic around the failed component via selecting new link path between the nodes of the failed link whereas path based methods employ end to end detouring of traffic by selecting new path between the nodes of the failed lightpath. These new paths are used as backup paths, i.e. protection paths.

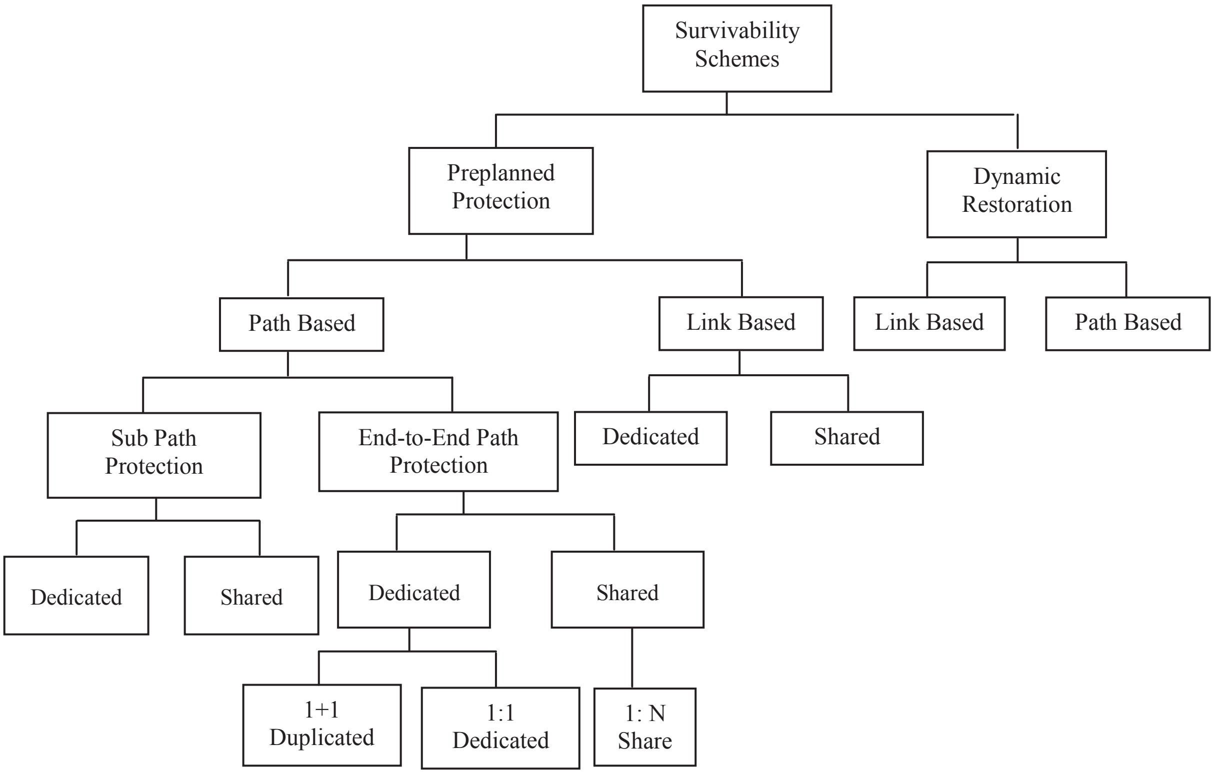


Figure 1.5: WDM Network's Survivability Schemes

In end-to-end path protection (also known as path protection) whenever a path fails, whole primary lightpath is replaced by its corresponding end to end secondary backup lightpath. Sometimes primary path can be partitioned into sub-paths, based on some network criteria [Cao2006]. In sub-path protection the failed sub-path is replaced by its secondary sub-path from the pre-computed sub paths [Ou2002] [Song2004]. Dedicated approach of path or link protection schemes use dedicated backup lightpath or link for the primary path to failure recovery while shared approach employs multiplexing techniques to share a single wavelength channel amongst backup of N working lightpath links. Traffic switched to protection lightpath links must be switched back again to the working primary lightpath links after repair making the availability of protection link to any future working primary link failures. In dedicated 1:1 path protection, backup resources are reserved in dedicated manner to the working primary path during the connection setup. These dedicated backup reserved resources can't be used for any other backup path of the other primary lightpaths. Traffic is switched to corresponding reserved backup path when failure occurs to primary lightpath. In duplicated 1+1 path protection, sender sends data simultaneously on both the primary path and to the backup path. The qualitative performance comparison of widely used fault tolerance schemes has been shown in Table 1.2.

Table 1.2: Qualitative performance comparison of survivability schemes

Schemes	**Recovery time**	**Recovery efficiency**	**Control overhead**	**Resource efficiency**
Dedicated path protection	very low	very high	very low	very low
Shared path protection	medium	high	medium	low
Dynamic path restoration	very high	low	very high	high
Shared link protection	low	high	low	medium
Dynamic link restoration	high	medium	high	very high

The major attention is on survivable routing design with protection approach for single link failure. Among all these survivable routing categories, shared protection is given more considerations because this has better resource utilization than dedicated protection. However, full path protection is easier to implement and has less complexity than link based and sub path based protection.

Overall network performance is influenced by the way information and network parameters are taken in routing decision. Generally, network performance is measured through the parameters like blocking probability, throughput, end to end delay, restoration efficiency, reliability, traffic load distribution, resource utilization etc. Therefore, it is required to develop appropriate intelligent survivable protection and restoration routing scheme, which maximize throughput and resource efficiency, minimize the blocking probability and data loss when a link failure occurs. Survivable routing performance of network is critically affected by the network's dynamic behaviour of how to determine and use lightpath to transport data from source to destination.

1.6 Objective of the Thesis

The operation and management cost of large networks lies on the deployed equipment, resource utilization and usage of energy efficient network management protocols. Performance management enabled with ensured quality of service needs suitable fault detection, resource management, survivability and re-configurability mechanisms [Maier2002] [Zhu2005]. Thus, reducing the network protocol cost in multichannel routed networks has become an important challenge for the network planners and engineers. The attempt to review the technologies and architectures to implement cost effective fiber network for efficient survivability mechanism in WDM networks further open issues to explore and resolve the existing challenges.

The high-speed optical WDM networks can carry large amount of data and that's why any of disruption caused by a network-related outage issues become an important area of concern among the researchers [Ramaswami2002] [Zhu2005] [Mukherjee2006] working in related area. Faults of communication network elements are inevitable. They may be implication of various challenges, including forces of nature (e.g., hurricanes, earthquakes), human errors (e.g., cable cuts), or malicious attacks. There is thus a justified need to provide the network with mechanisms of automatic reconfiguration to enable restoration of network services until faults of nodes or links are physically repaired. A single outage can disrupt millions of users and can result in huge traffic loss to limit the performance of the network and raises question on the network reliability. Mainly the failures are triggered or caused due to human or operator errors, however, component based failures are also significant. Thus, a systematic approach to simulate and evaluate the limitations of such failures in multichannel networks becomes an interesting field to investigate.

The most likely cause of link failures is fiber cut which needs the ability to reconfigure and reestablish communication upon such failure in WDM networks. Obviously, network survivability requires extra resource provisioning, fast switching capability, and efficient routing facilities at the control plane to reduce the restoration time. In WDM optical networks, such survivability can be achieved by setting up a link disjoint paths comprising of primary and backup lightpaths for each of the arriving connection requests between source and destination node pair. For the networks with connection requests arriving independently, it is important to develop a suite of interoperable strategies, which can provide a real-time solution for a link-disjoint working and protection path pair with sufficient capacity-efficiency. Hence, the problem of survivable routing and wavelength assignment becomes critically important for increasing the network performance of a survivable wavelength routed optical networks. The foremost important challenge of survivable optical networks is to devise efficient and intelligent routing mechanisms that can determine lightpaths such that the network’s total throughput performance is maximized while keeping the network resource usage at minimum for the given dynamic traffic demands.

The aim of this thesis is to achieve the following, research objectives:

1. To design and implement a lightpath survivability algorithm in optical WDM networks.
2. To design and implement algorithm through joint routing and channel assignment based approach for survivable WDM networks.
3. To develop a survivable lightpath routing through a nature inspired approach for the WDM networks.

1.7 Thesis Organization

A brief introduction of survivable routing strategies used in WDM optical networks are given in Chapter 1. The rest of the thesis has focused to meet the objectives of the study and strategies, which are presented in the following chapters:

Chapter 2: In this chapter a hybrid adaptive survivable routing mechanism is proposed. The proposed algorithm is influenced from the innumerable benefits of preplanned protection and restoration strategy to enhance the performance of WDM networks survivability. The pre-provisioned routes are analyzed and paths are dynamically chosen among them when one or more primary links may fail to restore the traffic. The prime aim of proposed integrated approach is to improve the system performance parameters in terms of blocking probability and restoration efficiency with reduced wastage of resources for dynamic traffic in WDM networks. The detailed simulation results are discussed which reveal that the proposed hybrid approach has an improvement in the network blocking performance and restoration efficiency. However, the demand of each user may not be of same nature and having dissimilar network service requirements in WDM optical networks. Thus, we have also considered the different categories of traffic services and proposed a scheme to enhance the performance of fault tolerance behavior of wavelength routed WDM network in the environment of multi-nature service and traffic. An analytical model for the multi-categorized traffic for distinct service level has been developed. The proposed strategy is analyzed to evaluate the performance of multi-categorized hybrid traffic under different combination of traffic scenarios. The simulation study confirms the superiority of multi-categorized traffic in terms of blocking performance and claims improved resource utilization.

Chapter 3: This chapter describes three survivable heuristic strategies of route selection for survivable wavelength routed optical WDM networks. One of the key challenges of survivable routing and wavelength assignment problem in WDM optical networks is to devise strategies to determine efficient primary and backup path to maximize the acceptance of incoming requests. These heuristic routing strategies are studied to describe the influence of the length of route on the blocking performance of survivable WDM network. Performance of these heuristic routing strategies have been analyzed through a detailed simulation study based on three scenarios, i.e. changing the network topology, load and wavelength availability per link in WDM networks. Simulation results have been discussed to reveal the comparative benefit of proposed algorithms. The findings have further been validated by comparing with the existing joint path pair selection strategy. However, the various rapidly growing services are bandwidth thirsty nature and consume huge energy. The energy consumptions expected to grow in near future rapidly due to drastically increased Internet users and legion new services. Thus, a resource and energy aware scheme has also been proposed to reduce the energy saving along with improved network blocking performance in a survivable optical network. The proposed algorithm under the constraint of resource and energy metrics shows superior blocking and energy consumption performance with respect to other compared strategies therein.

Chapter 4: In this chapter, a survivable lightpath routing and wavelength assignment strategy is modeled using maximum flow network problem of the graph theory. This approach determines wavelength and route together for incoming connection requests. Simulation results analyzed over three different network topologies confirm that the maximum network flow based lightpath routing for survivable network has significantly better call acceptance ratio as compared with conventional Fixed alternate routing, Shortest path and K-shortest path routing approaches.

Chapter 5: In this chapter, we have proposed an intelligent water drops based survivable routing mechanism for dynamic wavelength-routed WDM networks with single link failure model. A heuristic algorithm inspired from the intelligence behavior of swarms of intelligent water drops is designed, subsequently a framework is proposed to find the optimal link disjoint paths between a source-destination node pair. The effectiveness of proposed mechanism has been presented by carrying out comparative performance analysis with respect toconventional approaches, ant colony optimization and bee colony optimization based techniques.

Chapter 6: In this chapter, the thesis work has been concluded with the possible directions of the further avenues that may be explored.

CHAPTER - 2

Survivable WDM Networks: Adaptive Hybrid Approach

The Wavelength Division Multiplex optical networks become the best choice of providing the huge bandwidth requirement of next generation multimedia data communication networks by dynamically provisioning nearly countless bandwidth. The WDM networks have been widely deployed to provide high-speed internet services to the Internet users by incorporating wavelength reuse under suitable routing algorithm [Mukherjee1996]. The high capacity WDM network should be capable of maintaining service continuity even in the presence of faults within the network. In a wavelength-routed WDM network, a link failure can cause a severe service disruption and loss of data since large volume of traffic is carried by a single fiber. In accordance, the network survivability issue in the network transporting tremendous data traffic through hundreds of wavelengths in a single fiber becomes the important concern. Hence, a suitable fault tolerance mechanism is required for the survivable WDM network. However, the demand of each user may not be of same nature and having dissimilar network service requirements in WDM optical networks. Thus, network service operators can provide different services to satisfy the requirement of users and try to earn profit from the network. We have also considered the different categories of traffic services and proposed a scheme to enhance the performance of fault tolerance behavior of wavelength routed WDM network in the environment of multi-nature service and traffic in the last subsection of chapter.

2.1 Related Work

The WDM optical network is being widely and increasingly deployed everywhere in the next generation local area network, wide area network and even in the metropolitan area network [Ramaswami2002] [Mukherjee2006]. At present, Internet users are too much concerned of uninterrupted services. In the event of WDM network failures, large volume of data loss or delays in data can be experienced as each fiber has an aggregate bandwidth of the order of several hundred Gigabits per second. Therefore, service provider's concern is to focus their attention towards reliable networks, which can provide services even when failure occurs (i.e. cable cuts, node, link or channel fails, active components failure, etc.) in the networks [James2010]. Network's resilience to such failures can be achieved by providing additional resources to cope with the requirements of restoration process. Each working primary lightpath is associated with an alternate protection lightpath to overcome from the interrupted services. A connection request between the source and destination node is known as lightpath in the wavelength routed WDM network. During normal operation, a lightpath which is used to carry traffic is referred as primary lightpath. Hence, when a working primary lightpath is affected by a failure in the network, then the primary connection is required to be rerouted over a backup lightpath.

In WDM networks, routing and wavelength assignment mechanism incorporates fault aware capability to withstand from network failure. Various existing routing approaches have been attempted to address the issue of fault tolerance with an overhead cost of spare excess resource preprovisionings. Various routing mechanism of network survivability and its variations have been studied in literatures from different perspectives [Ramamurthy1999a] [Ramamurthy1999b] [Zhou2000]. Generally, preplanned protection and dynamic restoration are the two broad categorie of fault management strategies in wavelength routed WDM optical networks. Guaranteed recovery from certain type of failures in WDM networks are endorsed by Protection approach. However, in this mechanism pre reserved resources can be utilized for providing resilience may remain unused, thus, preprovisioned resources may be the wastage. Few advancement of protection mechanism based on shared path protection and p-cycles may optimize the resource utilization of backup paths with the reduced time of failure restoration [Kamal2010] [Eshoul2009] [Chow2004]. Dynamic restoration techniques do not utilize any form of preplanned network resource provisioning or any advance preplanning for recovery from the occurences of an event of failure in the WDM networks. It does not fully ensure any guarantee of recovery from a failure in optical networks in the dynamic traffic scenario [Ramamurthy1999b]. Dynamic Restoration usually involves longer recovery time in comparison to preplanned protection strategy. Both techniques can be implemented either on a link basis or on path basis. Path based approach is more capacity efficient than link based approach. Authors in [Miyao1998] suggested an Integer programming based design scheme of fast restoration, which can be achieved through predetermined dedicated or shared allocation of spare resources to the restoration paths for survivable WDM networks, such that the realtive facility cost is minimized. Comprehensive study in [Ramamurthy1999a] [Bonenfant1998] examines different approaches to protect mesh-based WDM optical networks from a single-link failures and determines the capacity requirements for a static traffic demand based on path/link protection/restoration survivability paradigms using integer programming based formulation. Author's in [Shao2006] [Shenai2005] proposed a scheme in which they combined the link protection with path protection strategy that gives better performance in terms of blocking probability in comparision to the pure path protection or link protection scheme. In [Ruan2010] a two link failure scenario has been handled intelligently by using the protection and restoration scheme. Similarly, in [Utama2015] both link based and subpath based restoration schemes are integrated to increase the survivability of network. These schemes choose the links or subpath on the basis of the recovery time of the link or sublightpath.

In [Wang2002] a partial path protection scheme based on amalgamated concept of path and link protection has been suggested. A dynamic restoration in which recovery paths and resources are determined in an adhoc manner after the occurrences of failure has been considered in [Grover1997] [Kaigala2003]. [Shenai2003] proposed a hybrid approach in which aggregate link information has been used to identify high risk critical links from which selectively most critical links are protected by restoration routes similar to the protection scheme. These selective links are protected by reserving backup resources proactively in advance. A selective segment based restoration technique is presented, in which critical segments are identified based on usage information in the network. Such segments are selectively protected as deemed necessary [Shenai2004]. Both of the approaches in [Shenai2003] [Shenai2004], proactively provides the protection only to few of the selective links or segments to achieve a balance between resource benefit and restoration efficiency at the cost of excess spare resources. These technique use the pre provisioned reserved bandwidth and routes for the restoration of the selective links or segments to re-route the disrupted traffic. If these reserved routes and bandwidth are not adequate to restore the affected traffic then restoration mechanism is used. So, the performance gain of both approaches depends on the reserved amount of wavelengths of the network which can utilized during the process of traffic restoration. In case, fault occurs to any link, segment or node which is not protected due to selective nature of protection in both the mechanisms recovery may not be guaranteed. The reserved wavelengths over the restoration routes may be the wastage of resources in case it goes unused and leaves fewer resources for the incoming traffic. It has been observed that faults generally do not occur frequently in practice so full reservation of resources not justified all the time. Every connection has not necessarily requires a fault tolerance capability to ensure network survivability in network and only few lightpath connections, critically requires survivable capability of fault tolerance [Shenai2005].

Hence, proposed mechanism should be capable to handle the restoration of interrupted services, which occurs due to multiple and different kind of failure in the networks. An integrated hybrid fault tolerance mechanism inspired from the combined strengths of preplanned protection and dynamic restoration technique is proposed in order to improve the efficiency of restoration with reduced wastage of resources for dynamic traffic in WDM networks.

In this chapter, a hybrid fault-tolerant mechanism is proposed that takes the possible multitudinous strength and benefit of both preprovisioned protection and dynamic restoration. Thus, it helps to improve the performance of the multichannel networks in case of dynamic traffic. The design objective of the proposed hybrid approach is to improve the capacity benefits, blocking probability and restoration efficiency with minimum wastage of network resources in dynamic traffic scenario. The simulation results have been confirmed that the proposed hybrid approach has improved the network blocking performance and restoration efficiency when compared to the traditional protection and dynamic restoration scheme.

2.2 Network Model and Problem Formulation

In this section, the network model used for hybrid routing with dynamic protection method has been discussed. A circuit-switched WDM networks have dynamic traffic sources such that connection requests arrive at a node based on the stochastic arrival process. In the network, nodes are equipped with WDM and wavelength cross connects. The physical fiber network is represented as a graph G (N,L,W), where N represents the number of nodes and L is used for the number of links in the network and each link has the same number of wavelengths channel W that each edge can accommodate. It is assumed that the bandwidth requirement of each connection request is one wavelength channel. Each node has a path table which can contain entries of list of K candidate route for each possible network destination nodes. Connection request matrix has been randomly generated at nodes in the network and only one connection request arrives at a time. Source and destination nodes are randomly chosen from the set of N nodes. There is no waiting queue, hence when a connection request is not able to establish due to network resources will be dropped from the network. The same wavelength is used over entire lightpath, that is, wavelength continuity constraint has been considered. We have considered a wavelength routed WDM network without wavelength converter at each node i.e. nodes are not equipped with the wavelength conversion capabilities.

The various notations and parameters considered for problem formulation are as follows:

Notations

N: Total number of nodes in the network

L: Set of links in the network

W: Total number of wavelengths on a fiber link

s, : Source node

d: Destination node

P: Set of existing primary lightpaths established between a source and destination nodes

p: A primary lightpath, $p \in P$

ρ_f: Set of all primary lightpaths affected by the possible link fault(s) f of edge (i,j)

(i, j): A link between node i to node j

Binary decision variables

$$\Psi_p^{s,d} = \begin{cases} 1, & if\ a\ backup\ path\ found\ for\ the\ primary\ lightpath\ p\ of\ node\ pair\ (s,d) \\ 0, & otherwise \end{cases}$$

$$\gamma_{p,(i,j)}^{s,d} = \begin{cases} 1, & if\ backup\ path\ of\ primary\ lightpath\ p\ of\ node\ pair\ (s,d)\ uses\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\varphi_{p,(i,j)}^{s,d} = \begin{cases} 1, & if\ primary\ lightpath\ p\ of\ node\ pair\ (s,d)\ uses\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\varphi_{p,(i,j)}^{s,d,w} = \begin{cases} 1, & if\ lightpath\ p\ of\ a\ node\ pair\ (s,d)\ uses\ wavelength\ \omega\ on\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\varphi_{p}^{s,d,w} = \begin{cases} 1, & if\ lightpath\ p\ between\ a\ node\ pair\ (s,d)\ occupies\ wavelength\ \omega \\ 0, & otherwise \end{cases}$$

2.2.1 Problem Formulation

The primary objective of the proposed approach is to determine the backup lightpaths for as many requests as possible for the existing primary lightpaths under the given capacity constraints of the links during the recovery process of restoration to provide fault tolerance capability to WDM optical networks. The design objective of the proposed approach is to maximize the restoration efficiency by minimizing the network resources for each connection request.

The objective of the problem can be written as:

$$\textbf{Maximize } \sum_{p=1}^{|P|} \Psi_p^{s,d} \ , \ \forall (s,d) \in N \tag{2.1}$$

Various constraints

i) Flow conservation for backup path of every primary lightpath p which guarantees that obtained solution gives a valid path from source s to destination d.

$$\sum_{j\in N} \gamma_{p,(i,j)}^{s,d} - \sum_{j\in N} \gamma_{(j,i)}^{s,d} = \begin{cases} 1\ , & if\ i = s \\ -1\ , & if\ i = d \\ 0\ , & if\ i \notin (s,d) \end{cases} \ , \forall\ \mathrm{i} \in \mathrm{N}, \forall\ \mathrm{p} \in \mathrm{P} \tag{2.2}$$

ii) Number of wavelength channels necessary to accommodate their backup path cannot exceed the number of wavelength channels available on links.

$$\sum_{p\in \rho_f} \gamma_{p,(i,j)}^{s,d} \leq W - \sum_{p=1}^{|P|} \varphi_{p,(i,j)}^{s,d} \ , \forall\ (\mathrm{i,j,s,d}) \in \mathrm{N} \tag{2.3}$$

iii) A primary lightpath consists of the same wavelength across all the traversing links of a path to enforce the wavelength continuity constraint.

$$\sum_{w\in \mathrm{W}} \varphi_{p}^{s,d,w} \leq 1 \ , \forall\ p \in \mathrm{P},\ (\mathrm{s,d}) \in \mathrm{N} \tag{2.4}$$

iv) A primary lightpath and its backup route must be edge disjoint routes.

$$\gamma_{p,(i,j)}^{s,d} + \gamma_{p,(j,i)}^{s,d} + \varphi_{p,(i,j)}^{s,d} \leq 1 \ , \forall\ (\mathrm{i,j,s,d}) \in \mathrm{N} \ , \forall \mathrm{p} \in \mathrm{P} \tag{2.5}$$

v) The primary path must be allocated the same channel number on each link in the path i.e. it must have exactly one wavelength associated with it.

$$\sum_{w\in \mathrm{W}} \varphi_{p}^{s,d,w} = 1 \ , \forall\ p \in \mathrm{P},\ (\mathrm{s,d}) \in \mathrm{N} \tag{2.6}$$

2.2.2 Cost Model of Link and Route

There are various ways of defining the cost of the link which can be based on network topology parameters, network resource utilization or combination of network topology and resource utilization. Network topology parameters based link cost can be defined in terms of physical path length, link cost, hop count, reliability, number or cost of optical devices, availability, number of converters or risk factor etc. The resource utilization based cost of link can defined in terms of available free wavelengths, busy wavelengths, ratio of available wavelengths and total wavelengths, ratio of busy wavelengths and total wavelengths etc. However, most of the cost models specify the cost of link or path in the form of combination of both network topology parameters and usage information of network resources. The integrated cost model of a link includes the available wavelengths and hop count, reliability and cost of link, load on the link and physical distance of link or busy wavelengths and physical link length, number of used wavelengths etc. In this work we have been used a combination of network topology and network resource based link cost definition which is similar to [Bhide2001] as shown below:

Considered notations are as follows:

W: Total number of wavelengths on fiber link.

$f_{i,j}^{a}$: Number of free wavelengths available on link (i, j).

$C_{i,j}$: cost of link (i, j).

B_p^K: Pool of set of K- protection backup routes corresponding to the primary path P.

H_{count}: Number of hops of a path.

Probability that a wavelength on link (i,j) will be available can be specified as

$$P_{i,j}^{a} = \frac{f_{i,j}^{a}}{W} \tag{2.7}$$

Probability that a wavelength on a link (i, j) will be used in future can be specified as

$$\rho_{i,j} = 1 - P_{i,j}^{a} \tag{2.8}$$

Probability that all wavelengths of the link (i,j) may be used at some time in future is represented as

$$\varphi = \left(\rho_{i,j}\right)^{P_{i,j}^{a}} \tag{2.9}$$

Availability probability of at least one wavelength in future on a link (i,j) is computed as:

$$\Phi = 1 - \varphi \tag{2.10}$$

Then the cost of a link(i,j) can be computed as

$$C_{i,j} = (1-\alpha) * 1 / H_{count} + \alpha(-\log \Phi) \tag{2.11}$$

here, α is control parameter which takes value of $0 \le \alpha \le 1$.

The cost of the end to end route can be defined as the sum of the traversed link cost of feasible path. Total cost of the route is computed as

$$P_{cost} = \sum_{i,j \in P} C_{i,j} \quad ,\forall\ (i, j) \in L \tag{2.12}$$

The above cost metric is used in order to obtain a good variation between multi path load balancing and network resource minimization.

Number of backup routes supposed to be pre-provisioned for a primary lightpath request p passing link (i,j) can be given as:

$$\beta^{kbr} = max_{\forall (i,j) \in p} \left(\Phi_{(i,j)}\right) \tag{2.13}$$

where $\Phi_{(i,j)}$ is total number of lightpath connection passing through link edge (i,j)

$$\Phi_{(i,j)} = \sum_{p \in P} \sum_{w \in W} \varphi^{s,d,w}_{p,(i,j)} \tag{2.14}$$

For each lightpath request, algorithm precomputes at least possible β^{kbr} number of routes which may be used during the restoration process after the service disruption to restore the disrupted working primary lightpath.

2.2.3 Model for Wavelength Assignment

In the wavelength assignment model, the binary variables used are as follows:

χ^{pw}_{mn}	Binary lightpath wavelength indicator variable that used to indicate whether lightpath p uses wavelength w on link (m,n) ; if yes, χ^{pw}_{mn} = 1; otherwise , χ^{pw}_{mn} = 0.
χ^{pwij}_{mn}	Binary lightpath wavelength link indicator variable that indicates whether lightpath p between nodes i and j uses wavelength w on link (m,n) ; if yes, χ^{pwij}_{mn} = 1; otherwise , χ^{pwij}_{mn} = 0.
χ^{ij}	Binary variable that indicates whether a physical link exists between node i and node j; if yes, χ^{ij} = 1; otherwise, χ^{ij} = 0.
χ^{p}_{mn}	Binary lightpath indicator variable that indicates whether there is lightpath from node m to node n; if yes, χ^{p}_{mn} = 1; otherwise, χ^{p}_{mn} = 0.

The wavelength assignment model assumed is similar to the model considered in [Sahu2006] [Bhanja2013]. The wavelength constraints concerned to the assignment of wavelength to lighpaths are as follows:

- Wavelength used by a lightpath is unique.

$$\chi^{p}_{mn} = \sum_{w=1}^{W} \chi^{pw}_{mn} \ , \forall (m,n) \tag{2.15}$$

- Wavelength continuity constraint.

$$\chi_{mn}^{pwij} \leq \chi_{mn}^{pw} \text{ , } \forall(\text{m,n}), \forall(\text{i,j}), \ \forall w \qquad (2.16)$$

- Two lightpaths cannot use the same wavelength on a link .

$$\sum_{m,n} \chi_{mn}^{pwij} \leq 1 \text{ , } \ \forall(\text{i,j}), \ \forall w \qquad (2.17)$$

- Ensure the conservation of wavelengths at the end nodes of physical links traversed by a lightpath.

$$\sum_{w}^{W} \sum_{i} \chi_{mn}^{pwij} \chi^{ij} - \sum_{w}^{W} \sum_{i} \chi_{mn}^{pwji} \chi^{ji} = \begin{cases} \chi_{mn}^{p} & \text{if } j = n \\ -\chi_{mn}^{p} & \text{if } j = m \\ 0 & \text{if} j \neq m, \quad j \neq n \end{cases} \qquad (2.18)$$

2.3 Adaptive Hybrid Protection Mechanism

An adaptive hybrid routing with protection mechanism is presented to improve the network resource utilization and restoration capability. The preplanned protection has assured recovery for all ongoing connections in the scenario of a single link failure model. This preplanned proactive protection mechanism reserves the wavelength resource of backup route during the establishment of primary lightpath of incoming connection requests [Ramamurthy1999a]. However, it has an ability to provide a guaranteed failure recovery, but in case of no failure, these pre-provisioned network resources will be unutilized and becomes wastage of resources. Other, widely used mechanism is dynamic restoration in which resources are searched and provisioned only after the failure has been occurred in the network. This mechanism does not ensure any guaranteed recovery of ongoing lightpath connections from the failure. Restoration approach is more resource efficient but takes more time to recover from failure scenario [Ramamurthy1999b]. These traditional protection and restoration schemes have their own strengths and weaknesses in terms of recovery time, network resource utilization, blocking probability, etc. These two mechanisms of survivability have innumerable advantages, however lack in resource utilization of the overall network capacity. The objective is to propose a mechanism which takes the possible strengths and benefits of both traditional mechanisms for improved network performance. The purpose of the proposed approach is to get better network performance, restorability, faster recovery, resource utilization with minimum wastage of network resources in the event of occurrence of failures in the WDM network.

2.3.1 Proposed Algorithm

Proposed mechanism proactively maintains a finite set of predetermined link disjoint paths for each primary path for a given source and destination node pair. For each incoming connection request, a primary lightpath is established and a set of link-disjoint preprovisioned backup routes are determined. Resources will be searched dynamically to establish a backup lightpath after the occurrence of failure from the provisioned pool of routes. This precomputed pool of backup routes in a node table will be utilized and paths are chosen among them to restore the traffic dynamically when one or more primary lightpath may fail. Pre-computed routes exist but channel bandwidth is assigned dynamically to one of these backup routes only to restore the failed traffic during the period of its existence. The network resources which are assigned to the failed primary lightpath will be pruned after its failure in order to make them available in the network to ease the recovery process. When path selected from those precomputed set is exhausted or no free channel is available on any of these paths, an attempt is conducted to recover from failure using dynamic restoration approach instead of dropping and rejecting the failed connection from the network. Hence, only required lightpaths can be given additional wavelength resource whenever required in the network. Hence, utilizing suitably both proactive and reactive methodologies together, the proposed mechanism has tried to achieve higher efficiency, better restoration and efficient utilization of the spare network resources. This scheme improves the capacity efficiency by allowing backup paths to assign channels after the occurrence of failures in the network. The complete process of proposed mechanism has been detailed by pseudo code shown below in Algorithm 2.1.

Algorithm 2.1: Adaptive Hybrid Protection Mechanism

Input: Physical network topology G(N, L,W); Set of arriving demands R_{sd}, whose source node s and destination node is d. Required bandwidth is a wavelength.

Output: Setup primary working Lightpath and K backup paths for survivable network

```
begin
 for (each incoming connection request $R_{sd}$ ) do
    Compute the link cost according to equation (2.11)
    Compute the least cost shortest path as primary working path
    Record all the free wavelengths along primary working path
    while ( free wavelength is not null) do
     Scan and select lowest indexed, first free available wavelength on each link
     if (same wavelength available in all the links ) then
```

```
        Update wavelength $W_\lambda$ along the primary working path
      else
          Block this current request demand.
          Go to the next incoming requests after three attempt.
      endif
    end while
  Eliminate channel assigned to the primary path
  Eliminates all the links used by the primary path from the network topology
    Compute the cost of links according to equation (2.11)
    Compute a pool of at least $\beta^{kbr}$ possible shortest candidate edge disjoint backup
        protection paths ($B^p_K$)
    Sort all paths in set $B^p_K$ whose route cost computed according to equation (2.12)
    Keep this arranged path set $B^p_K$ as backup paths for protection in B-route table
    Setup lightpath over the chosen primary path and selected wavelength
  end for
    Backup path pool updated regularly
  for (failure of working primary lightpath ) do
    Release all wavelength channels of failed working primary lightpath
    for (each k path of $B^p_K$ from B-route table of failed primary path) do
      if ( one or more free wavelength available on this path) then
        Choose a lowest indexed first free available wavelength
        if (same continuous wavelength available) then
          Update wavelength $W_\lambda$ along the chosen backup path
          Reroute the traffic over chosen backup path and selected wavelength
        endif
      endif
      if( $B^p_K == \Phi$ ) then
        Perform dynamic restoration process to compute a backup lightpath to
        restore the failed working lightpath
        if (restoration process unsuccessful) then
          The failed working primary lightpath is not restored and reject
        endif
      endif
    endfor
  endfor
end
```

2.4 Simulation and Performance Analysis

Extensive simulation has been conducted and the results are analysed to evaluate the performance of the proposed routing mechanism. In order to demonstrate the performance of the proposed approach, algorithm has been implemented in Java. A program is implemented to simulate the wavelength routed WDM network scenarios to validate the performance of the proposed algorithm(s). The implementation of the simulation program of the network scenario has been accomplished by various modules as shown in Figure 2.1.

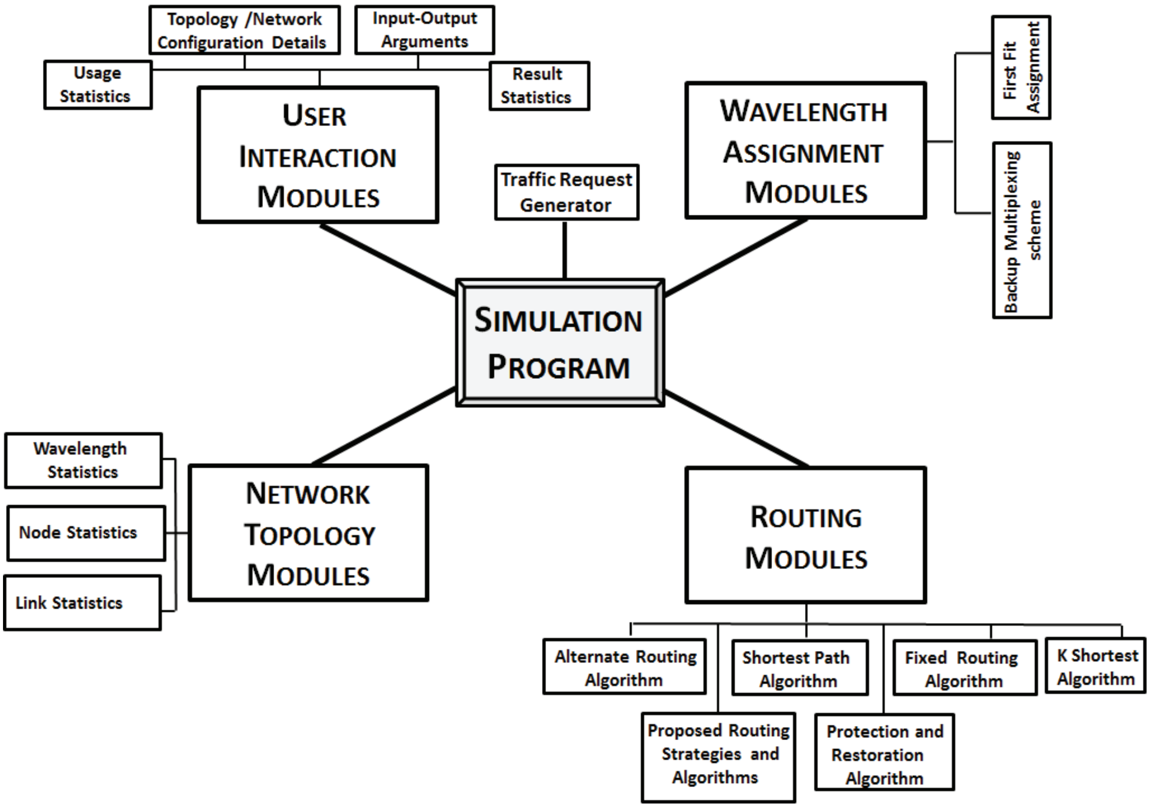


Figure 2.1: Modular Architecture of Simulation Program

For the studies of performance and analysis, simulation program has been developed using Java in eclipse development environment to model the behavior of wavelength routed WDM network. The simulation program consists of four major modules; Network Topology Generation, Wavelength Assignment Modules, Routing Modules and User Interaction Modules. Each module consists of the other sub-modules to handle a specific task of the simulation procedure. Routing modules implement codes of various route computation operations of routing process such as shortest path routing, K-shortest path, fixed alternate routing, protection/restoration algorithms and the proposed algorithms and schemes. Wavelength assignment module contains various wavelength assignment operations such as first fit algorithm and backup multiplexing strategy for shared resource assignment. This program takes various input configuration parameters such as network topology, connectivity information, channel information, traffic arrival and several other relevant network information and output the simulation result statistics. When the relevant details have been constructed, traffic between source and destination is generated randomly and appropriate proposed algorithm is executed and evaluated. It generate details of network information such as link, wavelength and node usage characteristics and result statistics such as lightpath established or blocked, details of call connections, wavelength and routing information, wavelength used, blocking probability etc. that computed through appropriate algorithm for the result analysis.

The program takes input parameter as number of nodes, links, and number of wavelength per link, link interconnection information and connection requests between random source-destination node pairs. In the simulation, primary paths with their corresponding disjoint backup path set have been computed. For incoming source destination node pair of requests, each source node establishes a primary lightpath and a set of possible link-disjoint backup path. First fit wavelength assignment model is implemented. In the first fit strategy wavelength resources are scanned starting from the lowest indexed wavelength and first free available wavelength is assigned. If a free wavelength is not available, the request is assumed to be blocked. The performance of the first fit scheme in terms of blocking probability and fairness is among the best [Zang2000] [Sun2003]. Therefore, first fit wavelength assignment startegy has been preferred among the other existing strategies. All links of the optical network topologies are assumed to have the same number of W wavelength channels. We consider dynamic traffic environment and assume that each connection requests arrive randomly with a random source and destination pair, one at a time and the connections which are established remains in the network for the duration of the experiment. The bandwidth requirement of each connection request is assumed to be one spare wavelength channel.

Furthermore, in order to evaluate the performance on different network scenarios with different characterstics, two test network topologies have been used which are shown in Figure 2.2a and Figure 2.2b. The network topology of Figure 2.2a has 13 nodes and

23 links with average nodal degree of 3.54. Each link in the test network topology of Figure 2.2a is assumed to have 8 wavelength channels. The topology in Figure 2.2b is NSFNET network, which consists of 14 nodes and 21 links with average nodal degree of 3. Both the considered topologies are nearly identical with a difference in average nodal degree. Each link in the test network topology of Figure 2.2b is also assumed to have 8 wavelength channels. Dynamic network traffic has been considered. Due to the simplicity we use first fit wavelength assignment heuristic for primary path and backup resource sharing concept for channel assignment has been considered for backup lightpath request. Each node is assumed to have no wavelength conversion capability. An unsatisfied connection request is considered as blocked and discarded from the network. Simulation has been performed for twenty times on each network topology and the obtained results have been averaged for the evaluation and analysis of the performance. Performance has been examined on the three scenarios i) changing the network topology ii) load and iii) total wavelength availability per link. Extensive simulation experiments that have been performed on the test network topologies indicate improvement in the network performance parameters.

2.4.1 Performance Metrics

Extensive simulation has been carried out to measure the following metrics for the performance evaluation over the considered network topologies for some of the typical network operating conditions.

Blocking probability: This metric is used to measure the network throughput performance. It is defined as the ratio of the number of rejected connection requests against the total number of connection requests generated in the network under dynamic traffic. This parameter is measured by simulation for the generated traffic of lightpath connection requests over the test network topologies and findings for such dynamic traffic presented in the next subsection.

Blocking probability improvement: This measurement is also an important criteria to have an idea about percentage improvement of Y's blocking probability against X's blocking probability. This can be specified as:

$$\mathrm{BPI} = \frac{\mathrm{BP_X} - \mathrm{BP_Y}}{\mathrm{BP_X}} \tag{2.19}$$

where, BP_X is blocking probability of strategy X and BP_Y is blocking probability of strategy Y.

Number of increased accepted calls: This metric depicts, how better one strategy may performs in terms of number of calls accepted in comparison to another strategy. It is defined as

$$IAC = R_X - R_Y \tag{2.20}$$

where R_X is number of lightpath calls accepted by strategy X and R_Y is number of lightpath calls accepted by Y.

Restoration probability: It gives an idea about restorable lightpaths that are affected due to failures. The restoration probability is defined as the probability that a failed connection can be restored successfully.

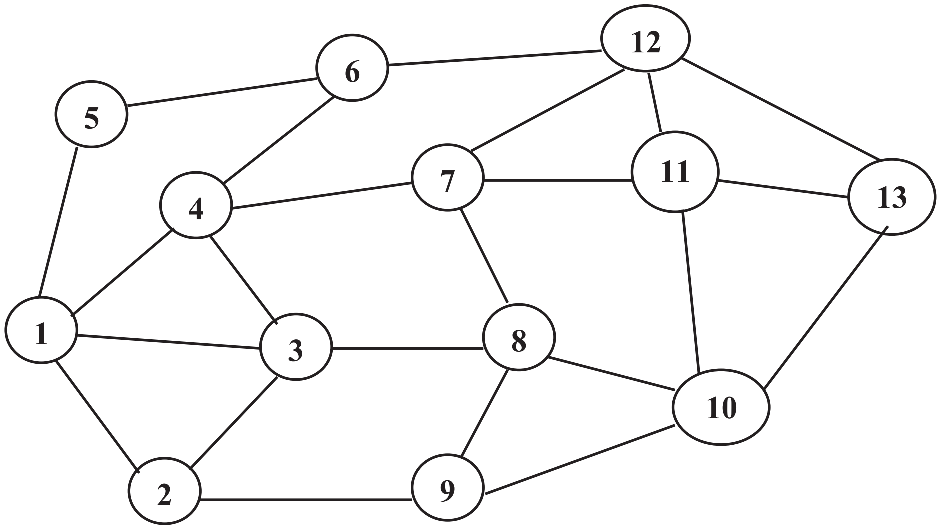


Figure 2.2a: Network Topology 1

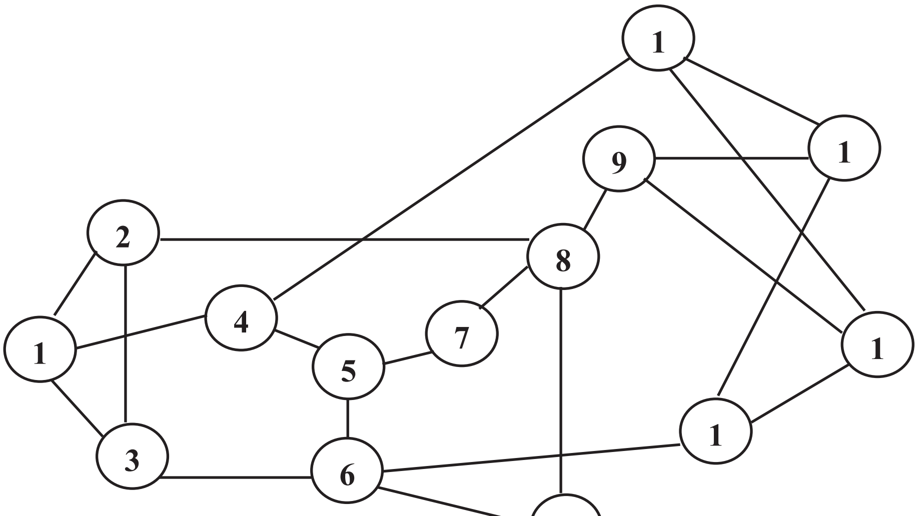


Figure 2.2b: Network Topology 2 [Huelsermann2004]

2.4.2 Analysis of Blocking Probability Performance

The effect of increased load of lightpath requests on call blocking probability has been evaluated under pre-planned protection routing, dynamic restoration routing and proposed hybrid routing strategy for the two considered network topologies.

In conventional solution the protection and restoration strategies have been extensively used. In the present analysis our proposed hybrid strategy has also been tested and compared with the conventional strategies. It has been found from Figure 2.3 that hybrid strategy is always superior to the dynamic restoration strategy and follows to the preplanned protection case with inferior values in the blocking probability performance measurement. It may be noted that preplanned protection shares the wavelength among the backup paths and may not ensure the failure recovery always and may lack 100% recoverability other than single link failure. The similar blocking performance parameter has also been computed for the considered network topology 2 and the results have been plotted in Figure 2.4. It is found that the qualitative performance behavior remain same.

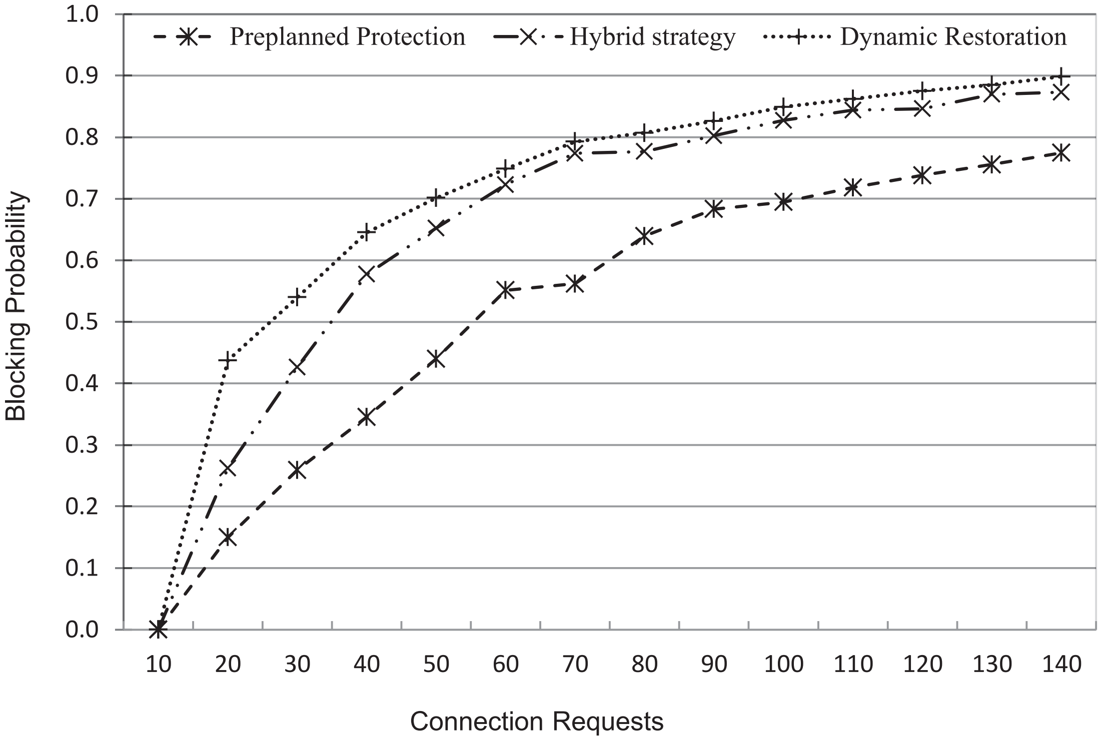


Figure 2.3: Blocking Performance on Network Topology 1

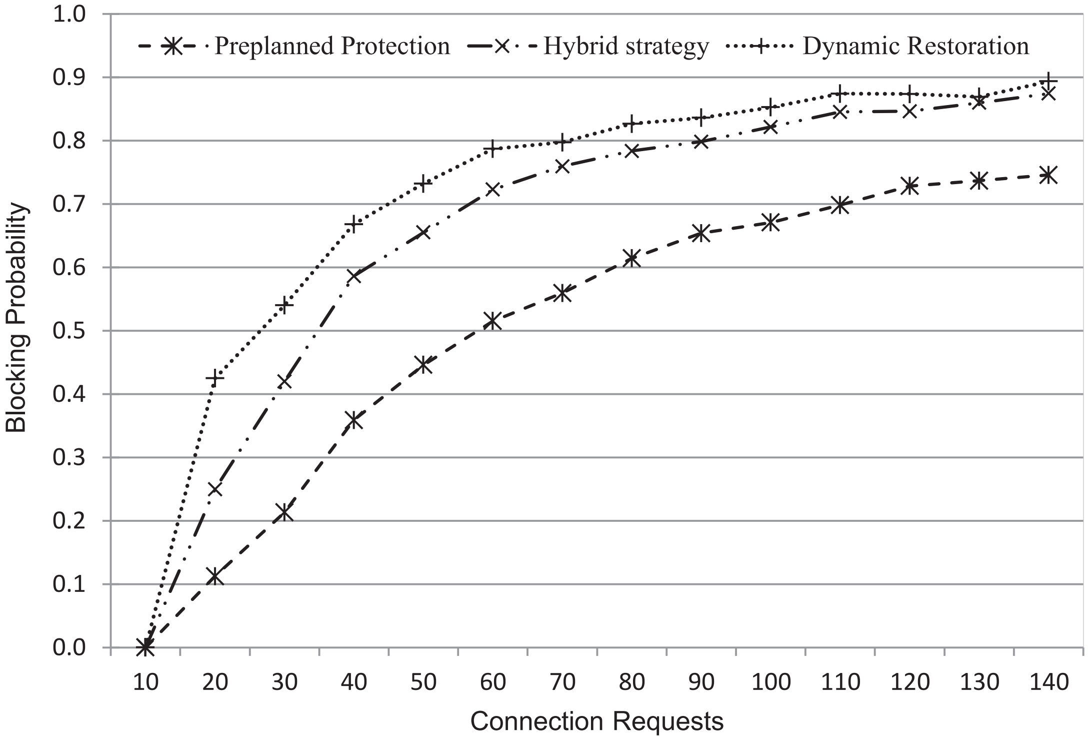


Figure 2.4: Blocking Performance on Network Topology 2

The simulation result also reveals that preplanned protection strategy is better in terms of blocking probability as compared to dynamic restoration and proposed hybrid strategy. It has also been observed from the graphs that the blocking probability of proposed hybrid strategy is lower and better than dynamic restoration strategy. It is observed from the results that the call blocking probability of all the three approache increases at higher lighpath traffic. The increase in blocking probability at higher lightpath traffic is observed due to the availability of less bandwidth resource at high arrival rate of requests in network. Thus, in the entire cases hybrid survival routing strategy is better than the dynamic restoration routing strategy in terms of blocking probability.

In the results of Figure 2.5 and Figure 2.6, the performance of the call blocking probability as a function of the number of wavelengths available per fiber on the network topologies have been presented for a traffic load of 250 lightpath requests. The results have been simulated for both the considered test network topology 1 and network topology 2 and are presented in Figure 2.5 and Figure 2.6 respectively. The graphs show that the blocking probability decreases when number of wavelengths per fiber link increases in both the network topology as expected due to enhanced resource. It is evident from the graphs that when number of wavelength resources in the network increases then the correspondingly blocking probability also reduces and this information is useful for the network management.

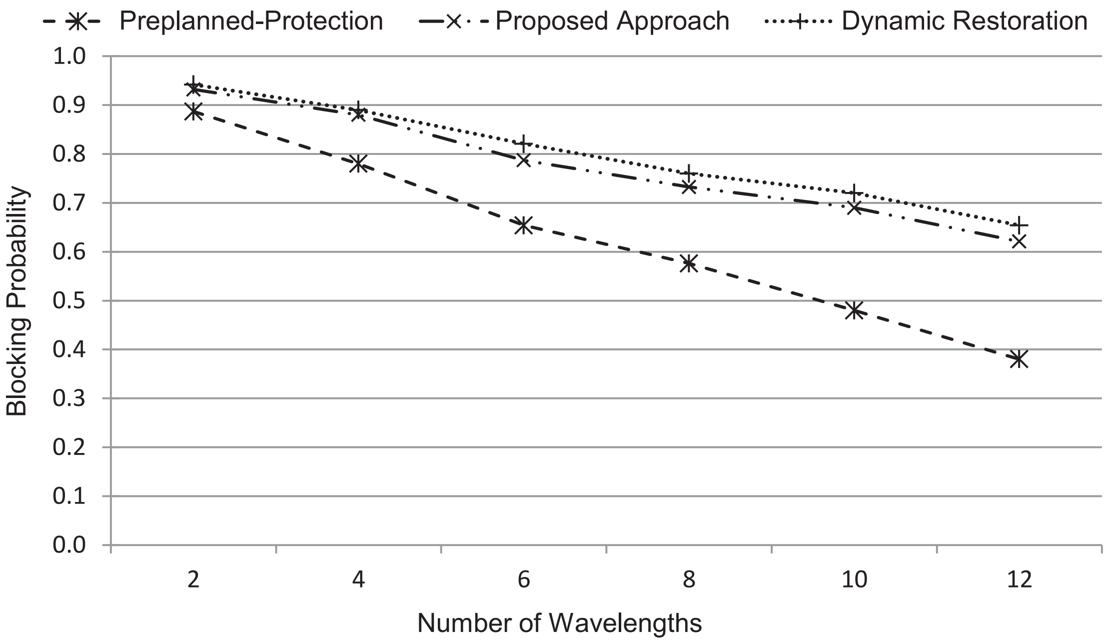


Figure 2.5: Blocking Performance Varying Number of Wavelengths on Topology 1

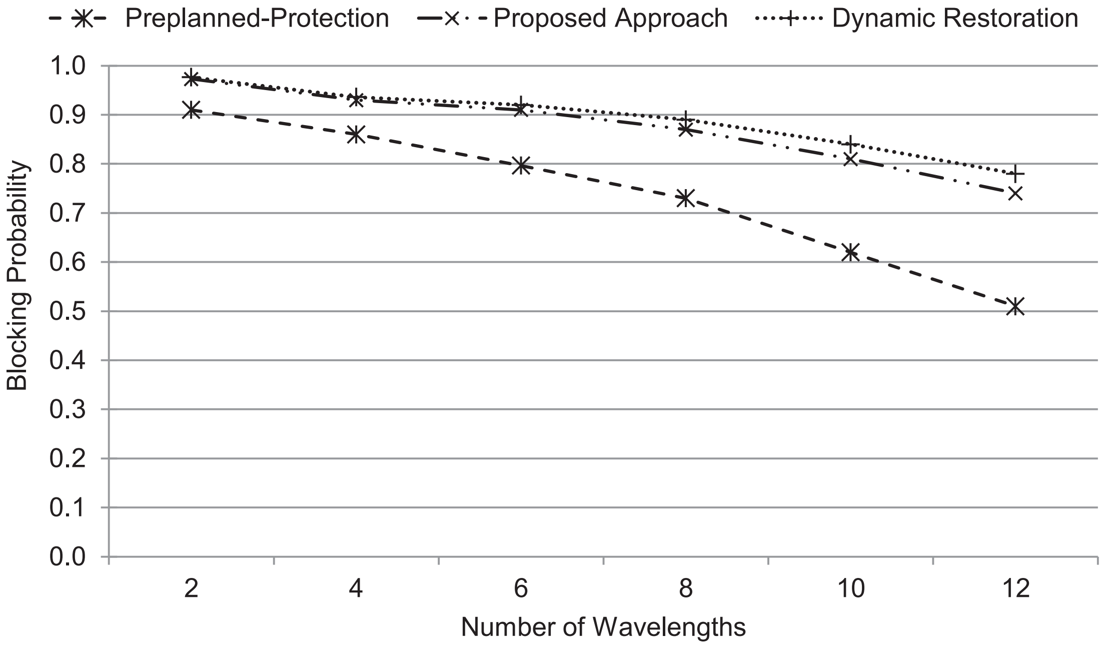


Figure 2.6: Blocking Performance Varying Number of Wavelengths on Topology 2

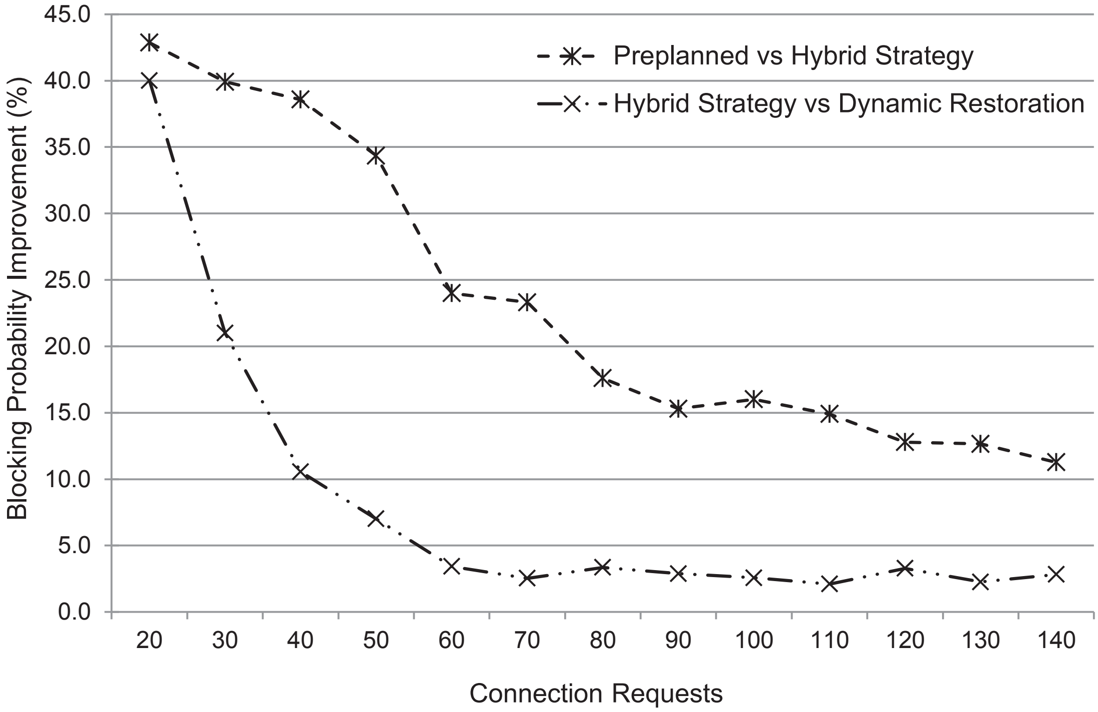
It is alo observed here that the blocking probability of hybrid strategy is lower than the dynamic restoration approach for a wide range of available wavelengths per fiber link. Proposed hybrid strategy performs better than dynamic restoration strategy while preplanned strategy performs better than other two strategies. These observations establish the superiority of the proposed scheme as compared to the dynamic restoration. The discusions and results confirm that for a better network performance wavelength resource has to be enhanced.

2.4.3 Analysis of Improvement of Blocking Probability Performance

The percentage improvement in the blocking probability of the proposed hybrid mechanism in comparison to dynamic restoration blocking probability on network topology 1 and toplogy 2 has been evaluated and presented in Figure 2.7, Figure 2.8 respectively. These graphs show some percentage improvement of preplanned protection blocking probability against blocking probability of proposed hybrid strategy on both the considered network topologies only at higher incoming lightpath requests, but with a compromise with the higher resource consumtion.

It is inferred from Figure 2.7 that in the case of proposed hybrid strategy, the blocking probability improvement decreases exponentially when lightpath requests increase in the network. The improvement in blocking probability of proposed hybrid strategy against dynamic restoration strategy has observed to be as high as 40% at low traffic load and at high traffic load it shows 3% benefit of improvement. Further from Figure 2.7, it is observed that the blocking probability improvement in case of preplanned strategy against hybrid strategy appears as high as 42% to 10% as the arriving lightpath requests increases in the network. Similar analysis for topology 2 has also been carried and the corresponding plots have been shown in Figure 2.8. The curve for this figure reveals that the proposed hybrid mechanism can improve the blocking probability performance only as 2% at higher lightpath requests and at low load it show 40% improvement against dynamic restoration strategy. Similarly the blocking probability improvement of preplanned strategy against proposed hybrid strategy also varies from 15% to 55%.

It has been observed from the above discussion made for Figure 2.3, Figure 2.4 and Figure 2.7 and Figure 2.8 that with the rise in lightpath requests, the network blocking probability increases, however, the corresponding blocking probability improvement decreases. It is observed that the rate of increase in blocking probability improvement is not commensurate with the corresponding increase in blocking probablity.



.**Figure 2.7: Performance of Blocking Probability Improvement on Topology 1**

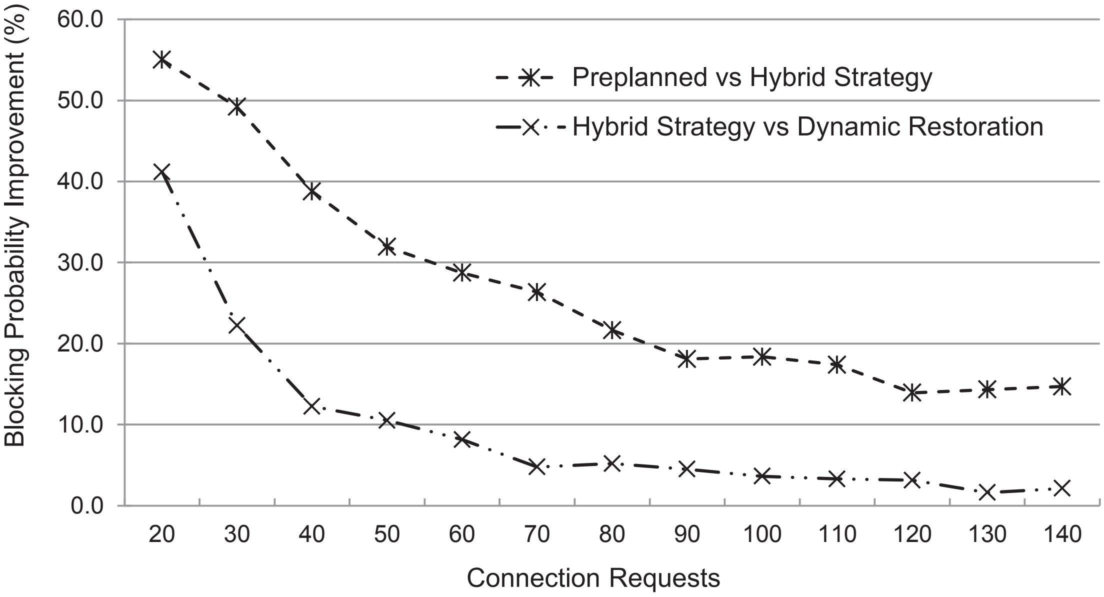


Figure 2.8: Performance of Blocking Probability Improvement on Topology 2

In general we may interpret from the graphs that percentage improvement of blocking probability decreases with the arriving lightpath requests and becomes stable at high load. In case of the proposed hybrid mechanism, it is inferred that it shows a balanced performance with respect to resource provisioning.

2.4.4 Analysis of Number of Increased Accepted Call Performance

In the network performance evaluation it is important to comment on the relative performance behavior for different applied strategies. The number of increased accepted call performance parameter depicts the relative quantitative improvement of one strategy over the other. This performance parameters for varying traffic of incoming lightpath requests for all the considered strategies in case of two representative network topologies have been simulated and the findings have been plotted in Figure 2.9 and Figure 2.10 respectively. Figure 2.9 shows that increased accepted call (IAC) performance of proposed hybrid approach is better over the dynamic restoration. It is also observed that the protection strategy supersedes over the performance of hybrid approach. One can also predict the performance of IAC of preplanned protection strategy which is better as compared to the dynamic restoration. This analysis confirms that the hybrid survivable routing mechanism can accomodate more lightpath requests as compared to restoration strategy which may attributed to the preprovisoned routes in case of hybrid strategy.

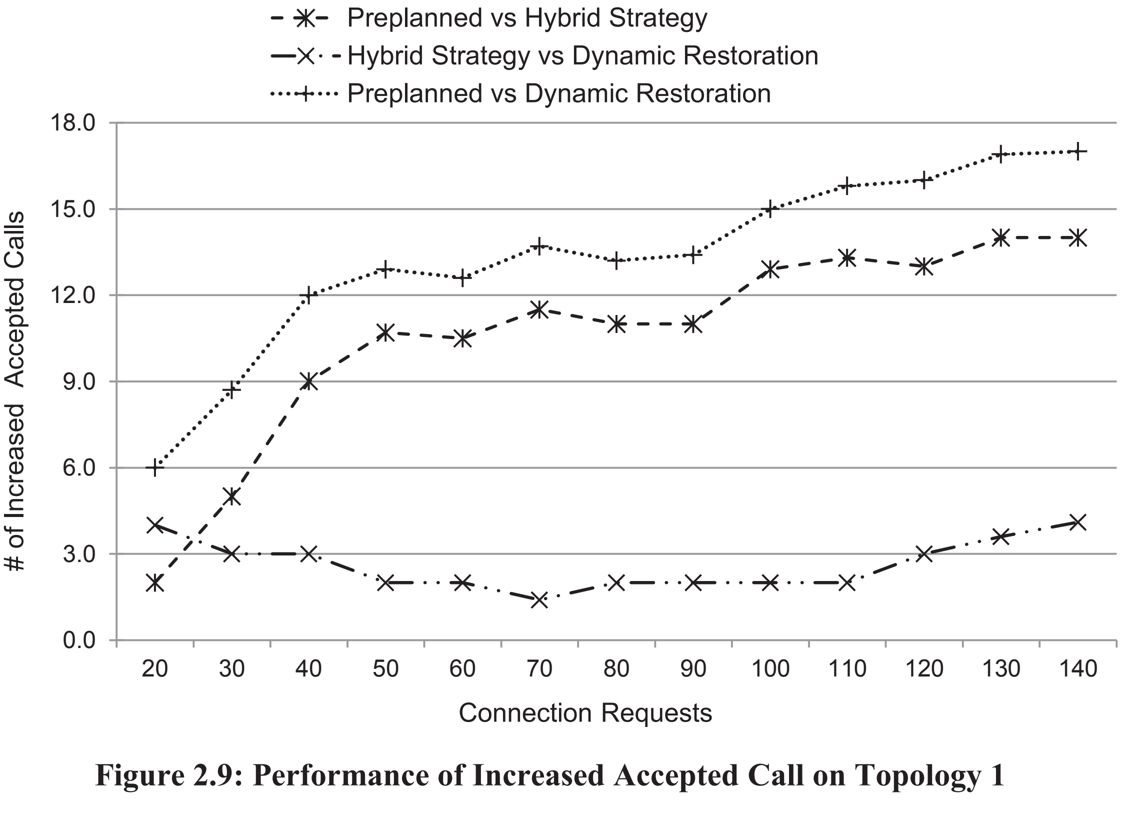


Figure 2.9: Performance of Increased Accepted Call on Topology 1

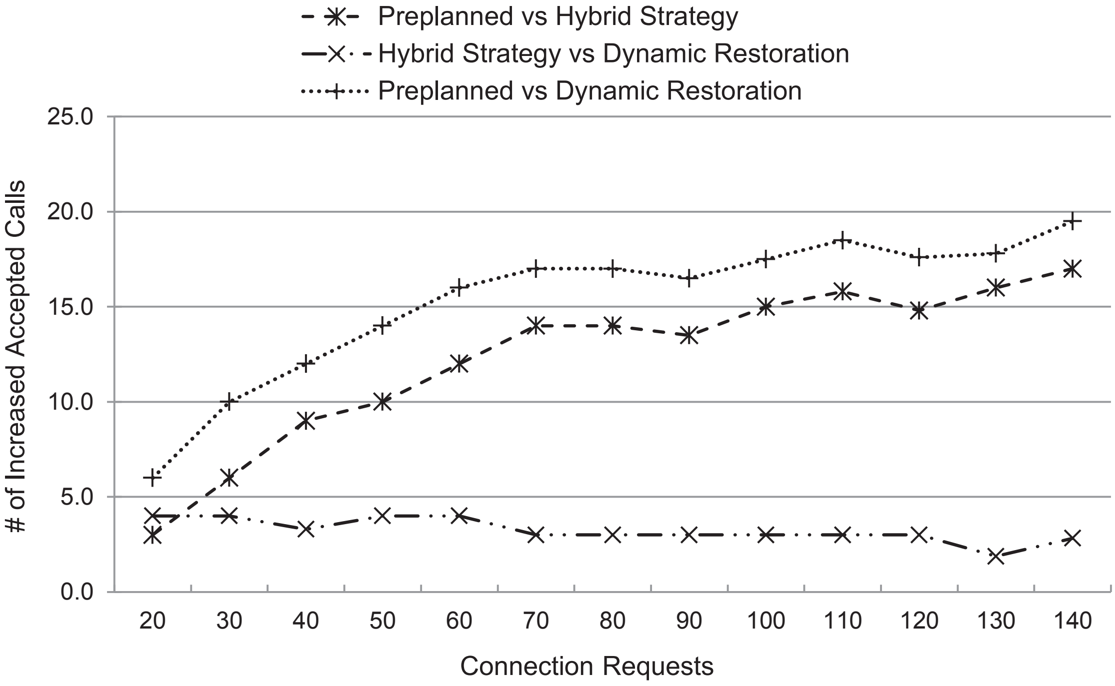


Figure 2.10: Performance of Increased Accepted Call on Topology 2

The IAC performance of hybrid approach varies as high as 5 more call request against dynamic restoration depending on network resource and traffic loads. It is found that in case of preplanned strategy against hybrid strategy IAC varies from 2 to 14. Similar behavior can also be observed in case of preplanned protection against dynamic restoration strategy. Similar analysis for all the above discussed strategy have also been made for topology 2 and presented in Figure 2.10. The curves in this resembles qualitatively with that of Figure 2.9. It has been observed from the results that proposed hybrid strategy accepts significantly more lightpath request as compared to dynamic restoration approach but inferior performance against preplanned strategy.

2.4.5 Analysis of Restoration Probability Performance

The efficiency of restoration performance in the considered topologies has been simulated for the proposed hybrid mechanism, preplanned protection and dynamic restoration scheme and the results have been presented in Figure 2.11 and Figure 2.12 respectively.

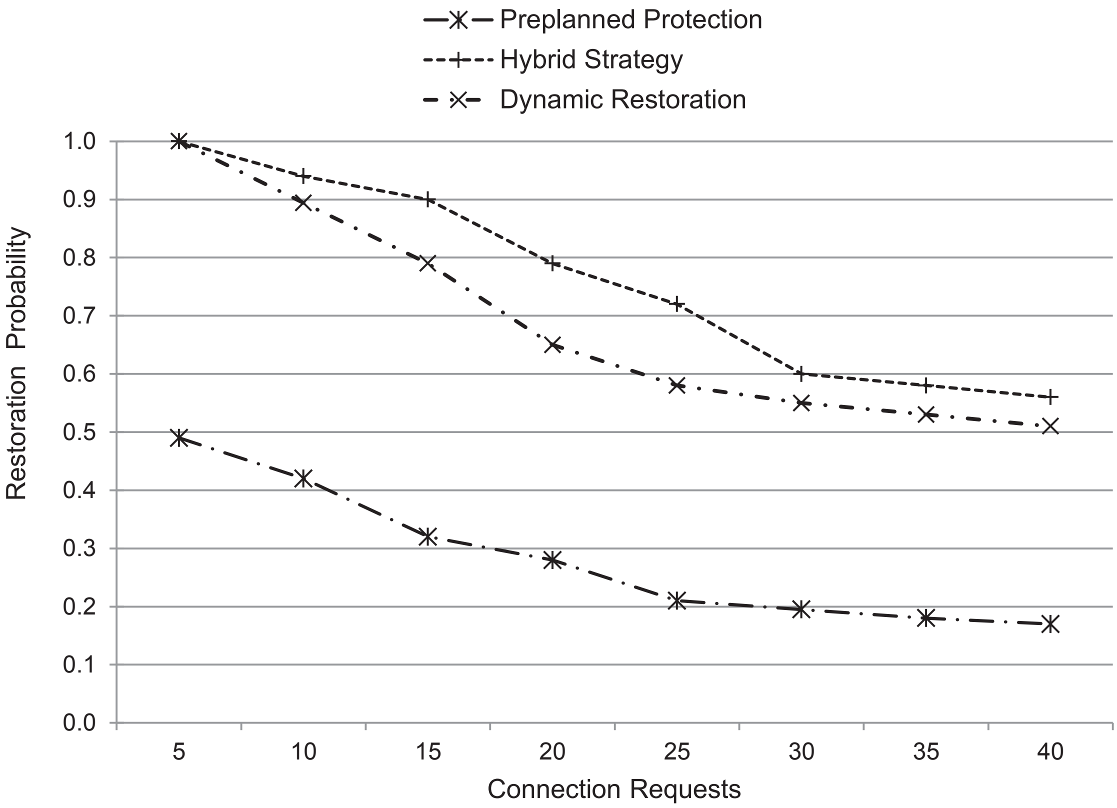


Figure 2.11: Restoration Probability on Network Topology 1

The nature of the curves for the restoration probability decreases with the increase of lightpath requests which is due to large lightpath request in the network. The simulation results for the restoration probability of proposed hybrid mechanism comes out to be better compared to the restoration and protection scheme. It is also inferred that at low arrival rate of requests, hybrid and dynamic restoration strategy restore almost all of failed lightpath traffic. This attributes to the availability of adequate resources at low traffic load. It is noted that at the higher traffic rate, the proposed hybrid approach claims a better restoration probability as compared to the other two cases. This may be attributed to the ability of hybrid approach to find the resources from preprovisoned backup path during the recovery process of failed lightpaths. This can be interpreted that in this case more wavelengths may be available from the failed working lightpaths. Similar observations have also been observed for topology 2, depicted in Figure 2.12. It is observed from these curves that hybrid mechanism shows consistent better performance as compared to protection and dynamic restoration strategy.

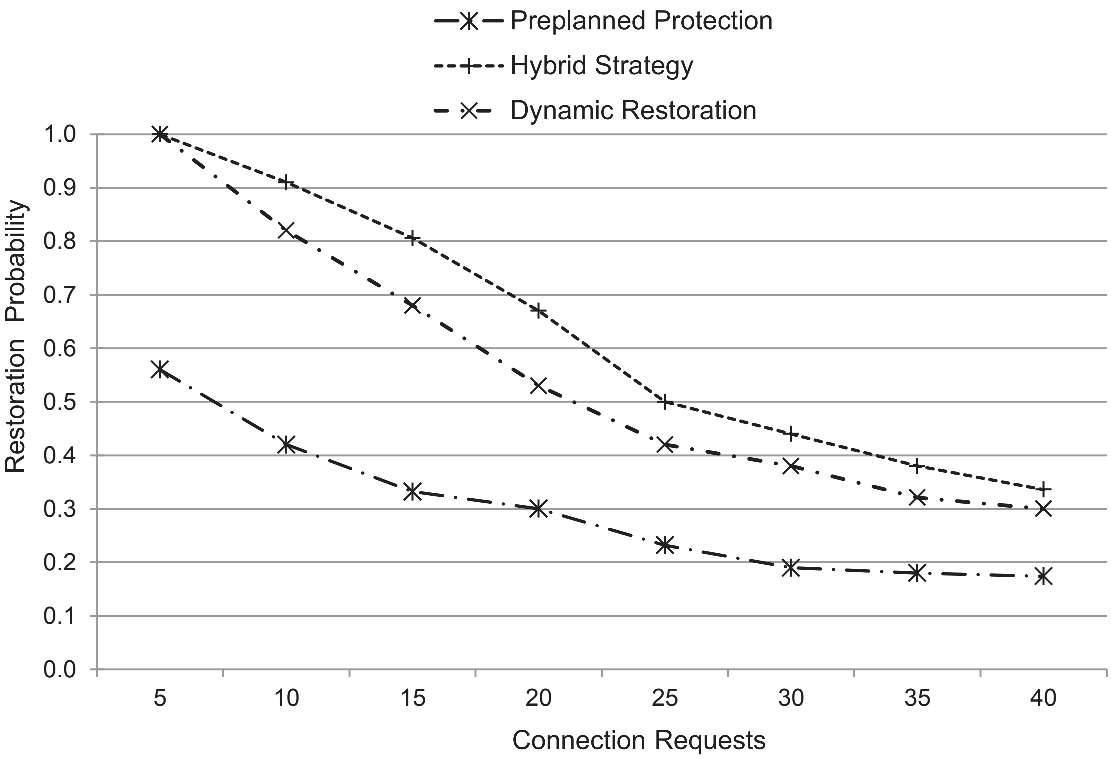


Figure 2.12: Restoration Probability on Network Topology 2

Thus, it may be concluded from the above discussion that the effectiveness of hybrid strategy in terms of efficiency of restoration probability is significantly better than the preplanned protection and dynamic restoration. The degradation of restoration performance of preplanned protection strategy at high traffic load is due to the non-availability of sufficient wavelength resources for the backup path. The proposed hybrid mechanism signifies a balance of high resource efficiency and better recovery to enable it as a viable solution for resource provisioning.

2.5 Survivability Approach for Multi-Categorized Hybrid Traffic

The ever growing demands of the user in a network can be satisfied with the optimal usage of the available resources of the network by taking care of the various level of traffic to cater the multi-services behaviour. Wavelength routed optical networks with wavelength-division multiplexing (WDM) technology have the capability of delivering an aggregate throughput in the order of Gigabits to Terabits per second. They appear as a viable approach for satisfying the ever-growing demand of more bandwidth per user on a sustained, long-term basis. An optical network architecture that appears promising for backbone networks is the one based on the concept of wavelength routing. Practically, different user connections may have a different type of service requirements and may need the service and bandwidth corresponding to their need. Due to the explosive growth of data related to Internet traffic, the next generation networks supposed to handle hybrid traffic of multiple types of multiservice nature such as data, multimedia, voice, etc. over WDM optical networks.

In Section 2.3, we have considered only one type of traffic and proposed an approach to enhance performance for fault tolerance behavior of wavelength routed WDM network. However, the demand of each user may not be of the same nature and having dissimilar network service requirements in WDM optical networks. Thus, network operators can provide different services to satisfy the requirement of users and try to earn revenue from the network. Network service diversification can be achieved by providing a different level of services to users for their demands. Today’s network as well as the next generation network is supposed to support multiservice instead of single service over the wavelength routed networks, where traffic is categorized into various levels based on users requirement. For example, real-time applications such as trading or financial transactions require zero data loss and immediate recovery; whereas video streaming services can tolerate the data loss and delay in recovery. Thus, they require differentiation in the treatment of service request in the network. The traffic requests that belong to distinct levels of service agreement; require different types of distinctions in trusted service provisioning among the traffic requests. Wavelength resources can also be used more effectively by using several levels of service guarantees or guarantee with the relaxation of smaller failure recovery. All these tailored distinctions in service may help to improve the use of network resources and network performance. The network service operator may generate profits in their revenue in a competitive environment from the different types of service assurance to accomplish the user requirements.

Next generation network requires to serve the network users with the various type of diversified services, each one having requirements of different degree of service quality. Various efforts have been made to provide differentiated services in WDM networks [Ren2010] [Muhammad2013] [Fawaz2004] [Abushaban2013] [Markidis2008] [Lee2007] [Vizcáıno2016]. In [Kantarci2009] and [Sukhni2008] an adaptive scheme based on differentiated availability for connection provisioning in optical networks has been attempted. Differentiated reliability based services for mesh networks with shared path protection have been suggested by the authors in [Tacca2003] [Jaekel2006] to provide resources according to the reliability requirements of users. But primary paths of certain services do not share the backup resource of high priority services. In [Fumagalli2006] author has been differentiated the connections based on the required degree of reliability of each individual connections and provides full protection or no protection based on the reliability degree chosen by clients in a WDM ring network. In [Jaekel2006] a mixed integer linear programming formulation has been presented for the dedicated protection, shared protection and unprotected type of different services in the network. In [GeZhihong2007] a mechanism of reusing the protection wavelengths in WDM ring networks based on the ranking of differentiated path availability has been presented. Authors in [Vizcaino2013] [Vizcáıno2016] have considered the differentiation in the protection quality at the level of routing with energy efficiency and protection switching time in the selection of protection schemes and considered the four different type of schemes considering the no protection, dedicated or shared survivability.

In [Szymanski2006] author has accomplished the service differentiation for two classes through the route management strategies for the optical network operator with little support from the control plane. In [Tzanakaki2008] two broad differentiation of survivability service in the form of dedicated and shared type of protection in WDM network has been attempted. In [Agrawal2017] service level agreement (SLA) for providing service quality at varying costs for flex-grid based elastic optical networks for different services has been proposed to improve the spectrum utilization from the network operator’s perspective. A backup resource assignment and routing selection strategy with reliability differentiated constraints has been proposed in [Guo2007]. This approach selects a route based on the reliability from the pre-selected set of three routes. In [Sukhni2008] author has considered the service based on the availability requirements against network failure to provide services in mesh networks. Authors in [Muhammad2013] have proposed a service differentiated provisioning in dynamic WDM networks based on the setup time and delay based service specifications for the users. In [Bhatt2017] author has been attempted to assign either dedicated protection, shared protection or no protection for the connection request based on the path length. Thus, the author has given the highest priority to long path length requests in terms of service without interruption. In [Chen2006] author has provided the congestion based differentiated service for different traffic using path inflation control policy to block a low priority label switched path requests. However, in the literature, mostly two to three service differentiations have been attempted without considering any current information of the network state dynamically. Each of them either provides survivability to the traffic or not providing any survivability. Different distinctions in the requirement of survivable service and differentiation among resources used by the traffic have not been attributed. In our approach, we have considered more than three levels of traffic categorization and also the network resource is distributed among the traffic categories to evaluate and understand the effect on the network performance.

2.5.1 Traffic Categories and Service Model

All network users may not always require same kind of network services and it will also be more expensive to avail such services. Thus, here, we consider and define four different categoriges for the level of traffic service that are supported in the optical WDM network and it has shown in Table 2.1. These traffic and level of services have been considered to observe that how the proposed strategy of multi-categorized traffic according to service requested by the user influences the network performance. Each arriving traffic request is divided into four traffic levels and each one has different type of service protection requirement as per the service level aggrement between user and service provider. Each category of traffic is served from the differentiated network resources for each category of traffic services. Thus, the connection requests of different traffic type are serviced by using the network resources based on the level of service requirement that is requested in the network. We have considered the following multi-categorized traffic into following different level according to service requirements of the arriving connection request is as follows:

Level-4 Traffic (L_4): For each connection setup a primary and SRLG disjoint backup lightpaths are assigned to the level-4 traffic category. Shared path resilient scheme is used in which link is protected to support single link failure with the tolerance to the dual link failure. Traffic of Level-1 connections can share the resources of backup lighpaths of level- 4 traffic.

Level-3 Traffic (L_3): For each lightpath request a primary and backup path are assigned. Backup path shares resource to other backup lightpath under backup-resource multiplexing constraint to sustain the situation pertain to single link failure. Backup routes can share resources with Level-1 traffic requests. When faults occur on primary route of level-3 traffic, ongoing connection switched to backup route automatically.

Level-2 Traffic (L_2): For each incoming lightpath request a primary lightpath is setup and no backup routes have pre-provisioned resources in advance to handle the failures in the primary lightpath. However, for enhanced restoration efficiency, this level of traffic use the hybrid restoration strategy of Section 2.4, Alogirithm 2.1. Thus, each primary lightpath is associated with a set of β^{kbr} link-disjoint backup paths which is used during restoration process to search for a wavelength among the reserved set to restore the failed traffic.

Level-1 Traffic (L_1): Each request of this level of traffic, setup only primary route that may use backup wavelength of higher level connections preferably. Requests of this category are not supported by any protection backup routes. When higher level of connection requests require to use the resources to restore the failed connection, the level L_1 traffic connection may be preempted to ensure that higher level of traffic can be restored.

Table 2.1: Traffic Categories and Feature of Level of Service Requirements

Type of → Service **Categories of Traffic ↓**	**Cost**	**Reliability**	**Failure handling**	**Shared Risk Link Disjointness**	**Survivability Requirement**	**Application**
L4-High	High	High	Dual failure Supportable	Supported	High	Real time Telemedicine application
L3-Moderate	Medium	Medium	Single failure Supportable	Partially Supported	Medium	Less critical Video/Audio streaming applications
L2-Medium	Low	Low	Not Guaranteed	No support	Low	Data-backup storage
L1-Low	Very Low	Un-supported	No support	No support	No Requirement	Non-realtime web surfing application

2.5.2 Assignment of Links Weight for Path Computation

In this section we describe the different cost factor which will be considered during the computation of primary or backup routes for different level of traffic in a multi-service network. The various notations and symbol used in formulation are shown in Table 2.2.

In a wavelength routed optical WDM networks during the provisioning of a lightpath for the primary or backup path, a link weight assignment function is used in the network of multi-level traffic categories.The weight of a link, $LC_p(i,j)$ is assigned to determine the primary route for the traffic of class level L_4, class level L_3 or class level L_2 request so that the links having more available wavelengths will be assigned low weight. The links that have no free available wavelength is assigned infinity cost.

In order to balance the traffic load and to avoid the congestions in the wavelength routed network the weight of each link for the computation of primary route is considered as:

$$LC_P(i,j) = \begin{cases} \infty & \text{if } W_f = 0 \\ 1 & \text{if } W_f = 1 \\ 0.1 * \left(\dfrac{W_t - W_f + 1}{W_t} \right) & \text{if } W_f > 1 \end{cases} \tag{2.21}$$

It can be observed in equation (2.21) that the weight of link reduces with an increase in the free wavelengths of the links. Thus, routing process will prefer the links that have more free wavelengths.

Table 2.2: Notations and Symbols Used in Formulations

Symbol/Notations	Description
$f(B)$	Failure probability of Backup path
$f(P)$	Failure probability of Primary path
P^n	Primary lighpath of nth request
B^n	Backup lighpath of nth request
$\lvert SRLG_{set} \rvert$	Contains set of all SRLGs of network
P^n_{SRLG}	SRLGs set of Primary lighpaths
B^n_{SRLG}	SRLGs set of backup lighpath
$V^*_{i,j}$	Reserved resource capacity required for backup on link(i,j)
$V^{k,l}_{i,j}$	Set of connections whose working primary lighpaths traverse link(k,l) and corresponding backup lightpath traverse link (i,j)
v^{λ}_{ij}	Set of wavelength links that will be in vulnerability when wavelength λ fails between (i,j)
B^{λ}_{ij}	Set of wavelength links that will be vulnerable when wavelength λ between (i,j) used by backup lightpath fails
P^{λ}_{ij}	Set of wavelength links that will be vulnerable when wavelength λ between (i,j) used by primary lightpath fails
W_t, W_f, W_{bs}	Total wavelengths, free wavelengths and backup shared wavelengths respectively.
$LC_B(i,j)$	Weight function for finding a backup path
$LC_p(i,j)$	Weight function for finding a primary path

For the better resource utilization, backup route traverse the links which have more reserved backup resources and having more available wavelengths in order to improve the call blocking by sharing of backup network resources. The weight of a link $LC_B(i,j)$ is used to determine the backup route which considers both the backup and free wavelengths of the network. The link weight $LC_B(i,j)$ for the backup route computation of traffic level L_3 can be adjusted as follows:

$$LC_B(\mathrm{i},\mathrm{j}) = \begin{cases} \infty & \text{if } \mathrm{W_f} + \mathrm{W_{bs}} = 0 \ \|\ \mathrm{W_f} + \mathrm{W_{bs}} < V_{i,j}^{*} \ \|\ (i,j) \in \mathrm{P} \\ \dfrac{\mathrm{W_t} - (\mathrm{W_f} + \mathrm{W_{bs}}) + 1}{\mathrm{W_t}} & \text{if } \mathrm{W_f} + \mathrm{W_{bs}} \geq V_{i,j}^{*} \ \&\&\ \mathrm{W_{bs}} < V_{i,j}^{*} \\ \delta & \text{if } \ \mathrm{W_{bs}} \geq V_{i,j}^{*} \end{cases} \tag{2.22}$$

Here, $\delta < 1$ is small positive constant set to 0.01. The required quantity of reserved backup wavelengths of link (i,j) can be given by $V_{i,j}^{*}$, which can be estimated as $V_{i,j}^{*} = \max\{\ |V_{i,j}^{k,l}|\ :\ \forall (k,l) \in E, (k,l) \neq (i,j)\ \}$. In equation 2.22, it can be observed that those links have smaller weight which has enough reserved and free wavelengths.Thus, if links of backup route has sufficient reserved backup wavelengths than there is no requirement of assignment of fresh wavelength and network resource utilization can be improved.

Link Failure Reliability

In WDM network a link consists of many components and it can fail if any component of the link fails. Thus, the probability of success (i.e. non-failure) of a link is the product of the probabilities of success of all individual components. Reliability of links is mapped from the network components and three different parameters were used are component failure in time (FIT), mean time between failure (MTBF) and mean failure time (MFT) and that can be determined using many techniques [Challita2005] [Glaesemann1992].

When R_l is reliability of a link *l* then the reliability of a primary path P can be given as,

$$R_P = \prod_{l \in P} R_l \tag{2.23}$$

Reliability of a backup path B can be calculated as

$$R_B = \prod_{l \in B} R_l \tag{2.24}$$

Reliability of a connection request which consists of both a primary and backup path can be computed as

$$R_{cnr} = R_P + (1 - R_P) * R_B \tag{2.25}$$

The probability that primary path and backup path may fail simultaneously can be given as

$$f(P \cap B) = f(\mathrm{P}) * f(\mathrm{B}) \tag{2.26}$$

The link failure probability for the single link failure can be extended to the shared risk [Guo2007] failure probability as;

Probability of failure of nth primary lightpath (P^n) can be computed as

$$f(P^n) = |P^n_{SRLG}| / |SRLG_{set}| \quad (2.27)$$

Probability of failure of backup path (B^n) of nth primary lightpath can be computed as

$$f(B^n) = |B^n_{SRLG}| / |SRLG_{set}| \quad (2.28)$$

Primary path reliability can be given as

$$\Re(P^n) = 1 - [|P^n_{SRLG}| / |SRLG_{set}|] \quad (2.29)$$

It can be observed from above equation that that when the number of the shared risk link groups of primary path will be smaller then the reliability of primary path will be larger.

The failure probability of primary and backup lighpath can be given as

$$f(P^n, B^n) = [P^n_{SRLG} \cap B^n_{SRLG}] / |SRLG_{set}| \quad (2.30)$$

The reliability of primary and backup lightpath can be expressed as

$$\Re(P^n, B^n) = 1 - [P^n_{SRLG} \cap B^n_{SRLG} / |SRLG_{set}|] \quad (2.31)$$

It may be observed from equation 2.31 that when overlapped shared risk link groups of primary and backup lightpath will be smaller than the combined reliability of both the routes will be higher. Based on the calculated reliability of both primary routes, the two backup paths can share the common backup wavelength resources even their primary routes are not amply links disjoint in the case of traffic of Level L_3 requests.

Shared Path Vulnerability of Dual Link Failure

Each lightpath traffic of level L_4 category is require to be protected with the policy of shared path protection strategy. In order to meliorate the dual link failure capability of class level L_4 traffic, we can reduce the vulnerability of shared path protection, when establishing the backup route for the traffic of level L_4 connection requests subject to double link failures.

Let V_{ij} be the set of links that will be in vulnerability when link (i,j) fails can given as:

$$V_{ij} = \bigcup_{\lambda \in W} v^{\lambda}_{ij} \quad (2.32)$$

here, v^{λ}_{ij} is set of wavelength links that will be in vulnerability when wavelength λ fails between node i and node j.

Set of links that will be vulnerable when all primary paths passing through link (i,j) fails can be estimated as:

$$V_{ij}^{P} = \bigcup_{\lambda \in W} P_{ij}^{\lambda} \tag{2.33}$$

here, P_{ij}^{λ} is set of wavelength links that will be vulnerable when wavelength λ between nodes i and j that has used by primary lightpath fails.

Set of links that will be vulnerable when all backup paths passing through link (i,j) fails can be estimated as:

$$V_{ij}^{B} = \bigcup_{\lambda \in W} B_{ij}^{\lambda} \tag{2.34}$$

here, B_{ij}^{λ} is set of wavelength links that will be vulnerable when wavelength λ between node i and node j used by backup lightpath fails.

Then, the set of links that will be in vulnerability when (i,j) link fails through which primary and backup paths passing can be computed as :

$$V_{ij} = V_{ij}^{p} \cup V_{ij}^{B} \tag{2.35}$$

The reduced network vulnerability can be achieved by reducing the number of links that are vulnerable in backup path links instead of links of primary path. This can be achieved by considering the number of vulnerable links $\chi_{m,n}^{\lambda}$ when λ wavelength fails between link $l(i,j)$ which can be computed as:

$$\chi_{m,n}^{\lambda} = \sum_{i,j} l(i,j) \quad \text{where } l(i,j) \in B_{ij}^{\lambda} \tag{2.36}$$

Thus, we should further avoid the backup sharing on the most vulnerable wavelengths link in the network to discourage any sudden huge quantity of vulnerable links on the backup route [Shao2008]. This will helps in reducing any dual link failure probability of shared protection of requests of class level L_4 traffic.

2.5.3 Analytical Model using Continuous Markov Model

In the figure 2.13 the general Markov Model of i+2 states space is shown in which each state represent number of busy resource on the links. State i represent here that ith resource used by system is busy, λ_i is arrival rate and μ_i service rate.

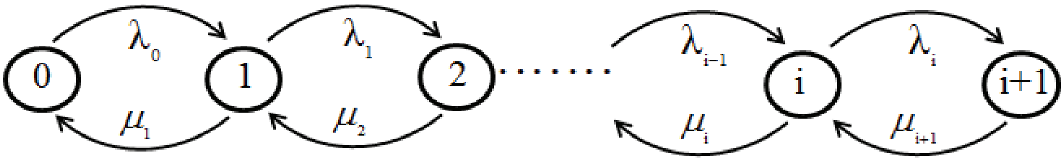


Figure 2.13: Basic Markov Model

Probabilities of steady state can be given as

$\Pi_i = \rho(i) = P[X = i]$

Where Π_i is probability that i unit of traffic load i.e. users are currently in X system process is either waiting in queue or being served.

Probabilities of all steady state can be given as:

Sate 0 : $\mu_1 \Pi_1 = \lambda_0 \Pi_0$ (2.37)

Sate 1 : $\mu_2 \Pi_2 + \lambda_0 \Pi_0 = (\lambda_1 + \mu_1)\Pi_1$ (2.38)

.

.

.

State i : $\mu_{i+1} \Pi_{i+1} + \lambda_{i-1} \Pi_{i-1} = (\lambda_i + \mu_i)\Pi_i$ (2.39)

From these equations, we can obtain

$$\Pi_1 = \frac{\lambda_0}{\mu_1}\Pi_0 \quad (2.40)$$

$$\Pi_2 = \Pi_0 \frac{\lambda_1 \lambda_0}{\mu_2 + \mu_2} \quad (2.41)$$

.

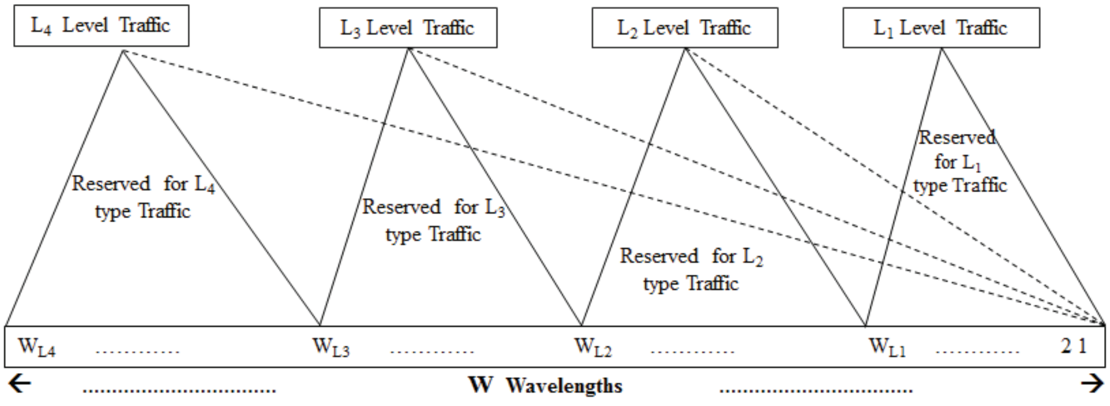
.

$$\Pi_{i+1} = \Pi_0 \frac{\lambda_i \lambda_{i-1} \lambda_{i-2} \cdots\cdots\cdots \lambda_0}{\mu_{i+1} \mu_i \mu_{i-1} \cdots\cdots\cdots \mu_1} \quad (2.42)$$

For existence of steady state $\sum \Pi_i = 1$ must be hold if and only if $\sum_{i=0}^{\infty} \Pi_{j=0}^{i} \frac{\lambda_j}{\mu_{j+1}}$ is finite such that

$$\Pi_0 = \frac{1}{1 + \sum_{i=0}^{\infty} \Pi_{j=0}^{i} \frac{\lambda_j}{\mu_{j+1}}} \quad (2.43)$$

This can be extended to finite state Markov model of transition diagram for our approach of categorized traffic level as shown in Figure 2.15. It has $W_{L4}+1$ state which correspond to total available wavelengths W in the system. Each state defines busy number of channel on the link and i^{th} state means i wavelength channel is busy i.e. not available. Here, same service rate μ is assumed and λ is arrival rate of traffic. Each traffic and finite channel resources are categorized into different traffic levels. In the system there are four different types of traffic levels as shown in the Table 2.3 and arriving lightpath request belongs to one of these levels of traffic. Each categories of traffic level is assigned different set of wavelengths of the total available wavelengths as shown in Table 2.3 and Figure 2.14. The traffic request of each level is generated in the network with proportions of different probabilities i.e. ρ_4 for L_4 class level, ρ_3 for L_3 class level, ρ_2 for L_2 class level and ρ_1 for L_1 level of traffic class. The requests on its arrival need to be served or instantly blocked i.e. rejected as there is no queue has been buildup of requests in wavelength routed network.



Here, $W_{L4} > W_{L3} > W_{L2} > W_{L1}$ and dashed line shows that lower level wavelengths can be used by higher level of traffic

Figure 2.14: Wavelengths Partition for Different Categories of Traffic

Table 2.3: Traffic and Wavelength Categories

Traffic Level	Wavelengths
L_4 –High	W_{L4}
L_3 -Moderate	W_{L3}
L_2 -Medium	W_{L2}
L_1 -Low	W_{L1}

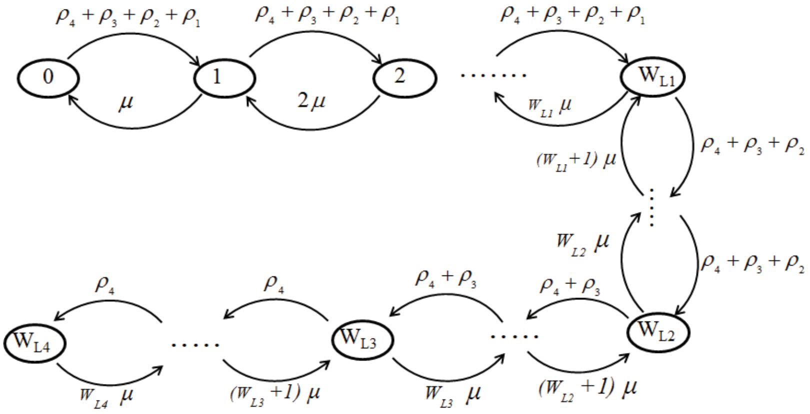


Figure 2.15: Markov Model for Multi-Categorized Traffic

Probabilities of all steady state balance equation can be given from state transition diagram as

$$iP(i)\mu = (\rho_4+\rho_3+\rho_2+\rho_1)\ P(i-1) \qquad \text{for}\quad 0 \le i \le W_{L1} \tag{2.44}$$

$$iP(i)\mu = (\rho_4+\rho_3+\rho_2)\ P(i-1) \qquad \text{for}\quad W_{L1} < i \le W_{L2} \tag{2.45}$$

$$iP(i)\mu = (\rho_4+\rho_3)\ P(i-1) \qquad \text{for}\quad W_{L2} < i \le W_{L3} \tag{2.46}$$

$$iP(i)\mu = \rho_4\ P(i-1) \qquad \text{for}\quad W_{L3} < i \le W_{L4} \tag{2.47}$$

For steady state, summation of all states can be given as $\sum_{i=0}^{W_{L4}} P(i) = 1$.

The probability $P(i)$ of steady states from these equations can be obtained as

$$P(i)=\begin{cases} P(0)\,\dfrac{(\rho_4+\rho_3+\rho_2+\rho_1)^{i}}{i!\,\mu^{i}} & \text{for } 0\le i\le W_{L1} \\ P(0)\,\dfrac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}}{i!\,\mu^{i}} & \text{for } W_{L1}< i\le W_{L2} \\ P(0)\,\dfrac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}(\rho_4+\rho_3)^{i-W_{L2}}}{i!\,\mu^{i}} & \text{for } W_{L2}< i\le W_{L3} \\ P(0)\,\dfrac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}\,(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}\,(\rho_4+\rho_3)^{i-W_{L2}}\,(\rho_4)^{i-W_{L3}}}{i!\,\mu^{i}} & \text{for } W_{L3}<i\le W_{L4} \end{cases} \tag{2.48}$$

here ,

$$P(0)=\frac{1}{\begin{array}{l}[\displaystyle\sum_{i=0}^{W_{L1}}\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{i}}{i!\,\mu^{i}}+\sum_{i=W_{L1}+1}^{W_{L2}}\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}\,(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}}{i!\,\mu^{i}}+\\ \displaystyle\sum_{i=W_{L2}+1}^{W_{L3}}\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}\,(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}(\rho_4+\rho_3)^{i-W_{L2}}}{i!\,\mu^{i}}+\\ \displaystyle\sum_{i=W_{L3}+1}^{W_{L4}}\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}\,(\rho_4+\rho_3+\rho_2)^{i-W_{L1}}(\rho_4+\rho_3)^{i-W_{L2}}\,(\rho_4)^{i-W_{L3}}}{i!\,\mu^{i}}]\end{array}} \tag{2.49}$$

From the above equations the blocking performance probability of traffic class of Level L_1 lightpath requests that can use allowable W_{L1} wavelengths from pool of W can be given as:

$$BP(L_1)=P(0)\,\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}}{W_{L1}!\,\mu^{W_{L1}}} \tag{2.50}$$

The blocking performance probability of traffic class type of Level L_2 lightpath requests which can use allowable wavelengths from 1 to W_{L2} of set of W channels given as:

$$BP(L_2)=P(0)\,\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}(\rho_4+\rho_3+\rho_2)^{W_{L2}-W_{L1}}}{W_{L2}!\,\mu^{W_{L2}}} \tag{2.51}$$

The blocking performance probability of traffic class level of L_3 type lightpath requests which can be allowd to use wavelengths from 1 to W_{L3} of pool of W channels can be deduced as:

$$BP(L_3)=P(0)\,\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{W_{L1}}\,(\rho_4+\rho_3+\rho_2)^{W_{L2}-W_{L1}}\,(\rho_4+\rho_3)^{W_{L3}-W_{L2}}}{W_{L3}!\,\mu^{W_{L3}}} \tag{2.52}$$

The blocking probability of traffic of type of high level L_4 requests which can be allowed to access all the wavelength channels can be inferred as:

$$BP(L_4) = \mathrm{P}(0)\,\frac{(\rho_4+\rho_3+\rho_2+\rho_1)^{\mathrm{W}_{L1}}\,(\rho_4+\rho_3+\rho_2)^{\mathrm{W}_{L2}-\mathrm{W}_{L1}}\,(\rho_4+\rho_3)^{\mathrm{W}_{L3}-\mathrm{W}_{L2}}\,(\rho_4)^{\mathrm{W}_{L4}-\mathrm{W}_{L3}}}{\mathrm{W}_{L4}!\,\mu^{\mathrm{W}_{L4}}} \tag{2.53}$$

Thus, these equations can be used to estimate the theoretical blocking probabilities of network under the different categories of traffic served by distinct set of wavelength resources in the network.

Now, we can use these expressions 2.50 to 2.53 to compute and analyze the theoretical behaviour of blocking probability in case of multi-categorized traffic and services in the network. These equations have been ploted using MATLAB 2018 platform under given traffic proportion of 35%, 25% for L4, L3 and 20 % for L2 and L1 respectively to understand the qualitative blocking behavior in a general network. The considered wavelenths are W_{L4}=8, W_{L3}=6, W_{L2}=4 and W_{L1}=2 and μ=20.

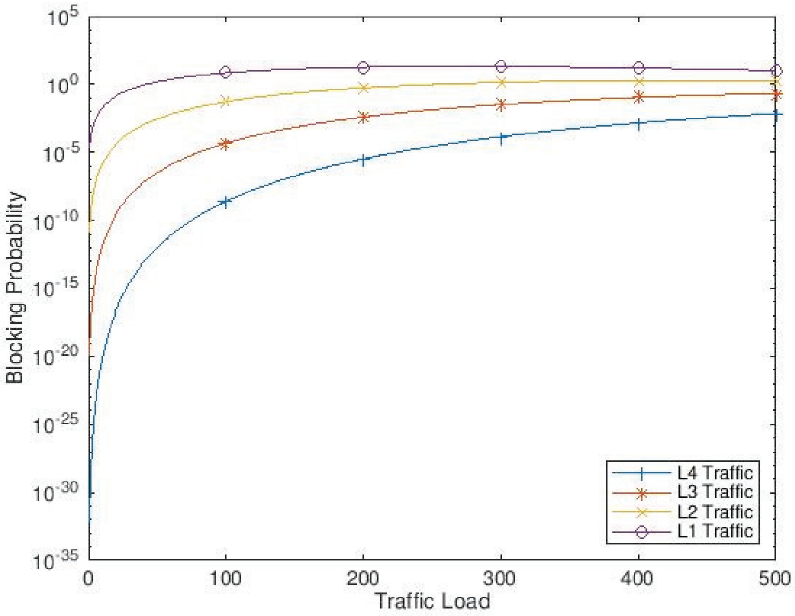


Figure 2.16: Comparative Blocking Probability Performance

The theoretical result has been plotted in Figure 2.16 and shows that the curve of blocking probability for L4 type of traffic is quantitatively lower but has similar qualitative behavior of other curves. Further, to analyse and understand the behavior of multicategorized traffic schenario in standard test network topology, an appropriate algorithm under these situations has been proposed in the next subsections.

2.5.4 Proposed Scheme for Multi-level Categorized Hybrid Traffic

In this scheme we have considered the problem of efficiently provisioning the multi categories of hybrid type of traffic with different level of service requirements in the environment of dynamic survivable wavelength routed network. The arriving traffic is partitioned in the different level of categories with distinct set of resources to provide services as per the requirement of different service level of users. The incoming requests are proviosned with a primary lighpath and assigned a backup lighpath protection in order to satisfy the service requirements of the connection on the basis of the categorized traffic type. The pseudo code of the proposed approach is given below in Algorithm 2.2.

Algorithm 2.2: Proposed Scheme to Handle Multi-Level Hybrid Type of Traffic

Input: Connection requests with category of traffic, Network Topology and Wavelengths Information
Output: Pair of primary and backups path or one primary path or NULL if no solution

```
Perform wavelength resource partitions for each level of traffic.
 For (each connection request $R_c(s,d,TrafficLevel)$do
  If (TrafficLevel =L4)
     Adjust link weight using equation (2.21).
     $PP_c \leftarrow$ FindShortestPath(s,d,G)  // Compute least cost shortest primary route.
     If ( ChannelAllocate($PP_c$)!=NULL) // Allocate wavelengths channel using First-Fit Assignment strategy
       PrimaryPath$\leftarrow$ $PP_c$
       If (primary path established)
       Compute weight of each link by calculating wavelength links vulnerability using
           equation (2.36)
         $BP_c \leftarrow$ FindShortestPath(s,d,G-$PP_c$)    // Compute link disjoint shortest backup route
         If (SharedChannelAllocate($BP_c$)!=NULL) // Assign wavelength channel
             BackupPath$\leftarrow$ $BP_c$
     else
         Block the connection request;
    Request$\leftarrow$ Next requests

  If (TrafficLevel =L3)
     Set link weight using equation (2.21).
     $PP_c \leftarrow$ FindShortestPath(s,d,G)  // Compute least cost shortest primary route.
     If (ChannelAllocate ($PP_c$)!=NULL) // Allocate wavelengths channel using First-Fit Assignment strategy
       PrimaryPath$\leftarrow$ $PP_c$          //   establish primary route P
       Adjust cost of link using equation (2.23).
       $BP_c \leftarrow$ FindShortestPath(s,d,G-$PP_c$) // Compute shortest disjoint backup route
      Compute combined reliability of primary paths $\Re(WP_c, WP_n)$ using equation (2.31).
       If ( $\Re(WP_c, WP_n) >= \delta$ )
           If ( $PP_c \cap PP_n \neq \Phi$ )
             If (ShareChannelAllocate($BP_c$)!=NULL) //Assign wavelengths such that Backup paths can
                                    share common backup wavelengths even primary paths are not disjoint
```

```
            BackupPath← $BP_c$
        else
            If (SharedChannelAllocate($BP_c$)!=NULL)   //Assign wavelength using backup wavelength
                                                       multiplexing strategy
            BackupPath← $BP_c$
        Else
            Block the connection request;
        Request←Next requests
If (TrafficLevel =L2)
    Set link weight using equation (2.21).
        $PP_c$← FindShortestPath(s,d,G)  // Compute least cost shortest primary route.
    If (ChannelAllocate ($PP_c$)!=NULL) // Allocate wavelengths channel using First-Fit Assignment strategy
            PrimaryPath← $PP_c$          //  Assign wavelength channel and establish primary route P
    K-Paths ← Find_K-ShortestPath(s,d,G-$PP_c$) // Compute K-shortest disjoint backup route
    Record set of K-Paths for restoration process
    else
        Block the connection request;
    Request←Next requests
If (TrafficLevel =L1)
    Set link weight using equation (2.22).
    $PP_c$← FindShortestPath(s,d,G)  // Compute least cost shortest primary route.
    If (WavelengthAllocate($PP_c$)!=NULL) // Allocate wavelengths channel using reserved backup
        PrimaryPath← $PP_c$                  wavelengths preferably
    Request←Next requests
End
```

2.5.5 Performance Analysis

We have performed the simulation to evaluate the performance of the proposed approach on US network topology shown in Figure 2.17 consists of 15 nodes and 26 links [Guo2004]. In the simulation model each of the nodes in the network is capable to generate lightpath request to a random destination node. Each link in the network assumed to have same wavelength channels i.e. W=15. Assume that connection requests arrive for a random source and destination pair. The traffic request and service category for each connection has been generated randomly. Reliablity probability of each link is randomly distributed between 0.98-0.99. The bandwidth required for each connection request is satisfied by one wavelength. Lightpaths follow wavelength continuity constraint and incremental traffic has been assumed such that that each request arrive one by one in network and their holding time is long enough to consider that established lightpaths do not leave.

A connection request is blocked if either primary or backup path cannot be setup. Results that are shown in the plots are the average values over ten independent simulation runs for the evaluation of network performance. Lightpath request can be setup if the same wavelength is free on all the links used by the request; otherwise, the request is blocked. If a connection requests can be accommodated, it is assigned one of the first indexed wavelength that is available on the links used by the lightpath request. For primary path First Fit wavelength assignment algorithm is used and backup multiplexing technique has been used for channel assignment to backup paths. Wavelength W=15 is assigned to the categorized traffic as W_{L4}=6, W_{L3}=4, W_{L2}=3 and W_{L1}=2. In all figure "Li(y%), indicates that traffic of level i category occupies *y* percentage of the total traffic of connection requests in the network. Traffic percentage always represented in the order of L4, L3, L2, L1 level of traffic wherever required for all traffics.

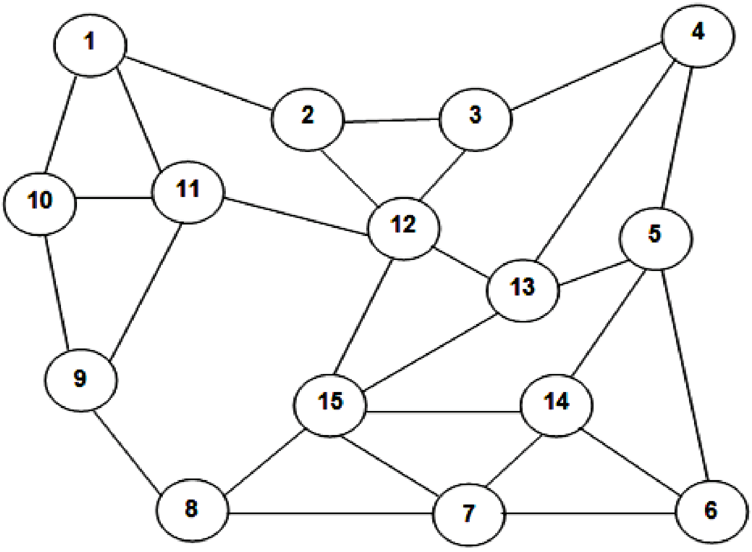


Figure 2.17: US Network Topology

The performance of the call connection blocking probability has been evaluated under proposed algorithm 2.2 as a function of incoming connection traffic request on the USIP network topology. In the simulation we have first assumed the higest level of L4 traffic of 35% of the network traffic keeping the traffic proportions of L3, L2 and L1 as 25%, 20%, 20% respectively to observe the blocking behaviours of different level of traffics. The findings of the simulation results have been presented in Figure 2.18. The graph shows that the blocking probability corresponding to L4 level traffic is lowest as compared to the bocking performance of the other three compared cases therein. This findings confirms the qualitative behavior of the results obtained in Figure 2.16. Traffic of level L1 has the worst blocking probability performance. The reason attributed to this is that traffic of L4 category has been assigned more resources and it can also use the resources of other lower level of traffic due to its priority privilege for the services.

However, Traffic L1 level is of lowest service category and has less resources as compared to other higher level of traffic categories. Blocking probability of L3 level traffic is less compared to L2 and L1. L1 level traffic uses backup resources of the higher level of traffic which can not deteriorate the performance significantly at high traffic load.

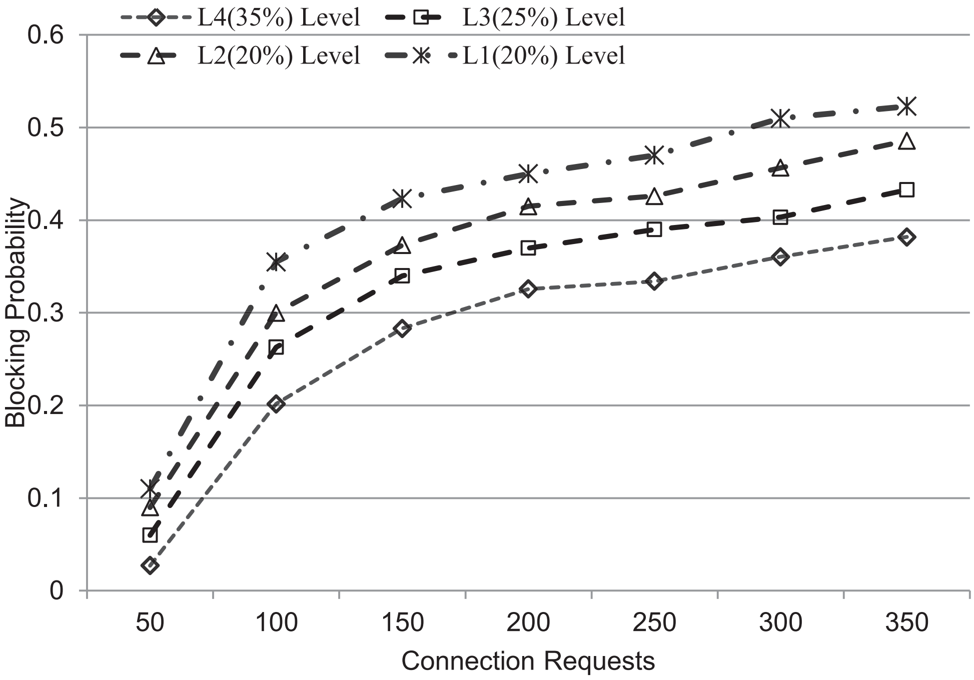


Figure 2.18: Blocking Probability of Different Categories (35%, 25%, 20%, 20%) of Traffic

Further, the network performance for varying the contribution of different percentage of traffic in each level for services has also been evaluated. The plots of Figure 2.19 and Figure 2.20, the blocking probability performance of all foure level of traffic is analysed for the relative traffic percentage of (L4-25%, L3-35%, L2-20%, L1-20%) and (L4-20%, L3-20%, L2-35%, L1-25%) respectively. In both the cases, plot of L4 level of traffic has lowest blocking performance while L1 has the worst blocking probability performance. It is noted that reduction of traffic in L4 improves its blocking while the overall qualitative behavior with respect to incoming traffic remains similar for all the other cases. The simulation curves of Figure 2.19 and 2.20 for case of L1 for traffic variation of 20% to 25% shows still higher blocking compared to other cases. In Figure 2.19 and Figure 2.20 the blocking performance of L2 and L1 traffic is significantly higher due to increased traffic load of same category and less resource availability in the network for them.

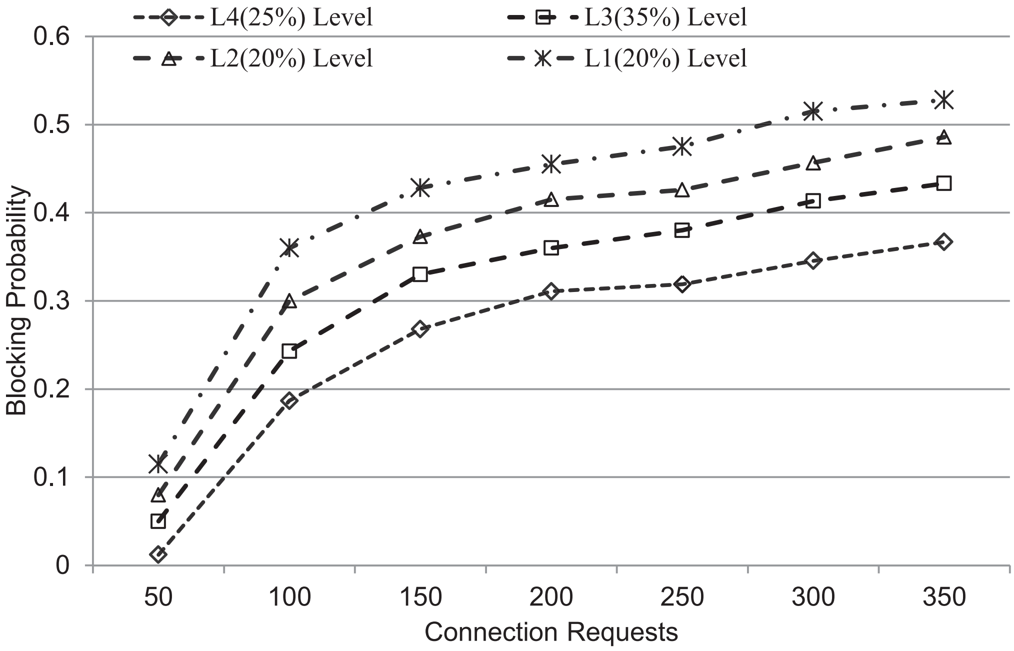


Figure 2.19: Blocking Probability of Different Categories (25%, 35, %20%, 20%) of Traffic

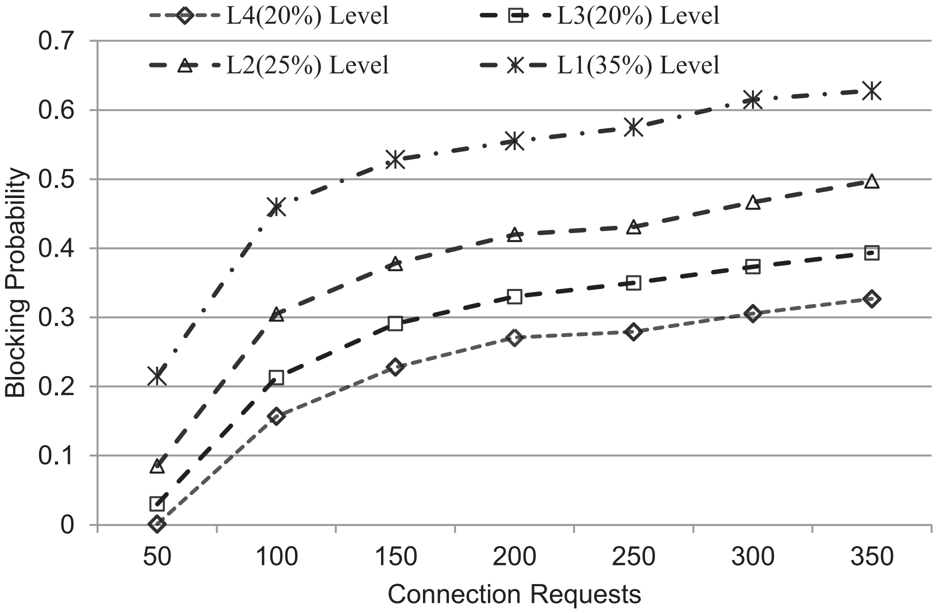


Figure 2.20: Blocking Probability of Different Categories (20%, 20%, 35%, 25%) of Traffic

The above discussion has been for the case of coexistence of all the four level of traffic with varying traffic proportions of categorized traffic. It has been observed from the discussion that different level of traffic imposes different blocking behavior and therefore, we attempt to compare the behavior of the hybrid level of traffic scenarios with that of traffic having all the traffic either L4 or L3 type.

Now, we will analyze the performance of the proposed strategy for multilevel hybrid

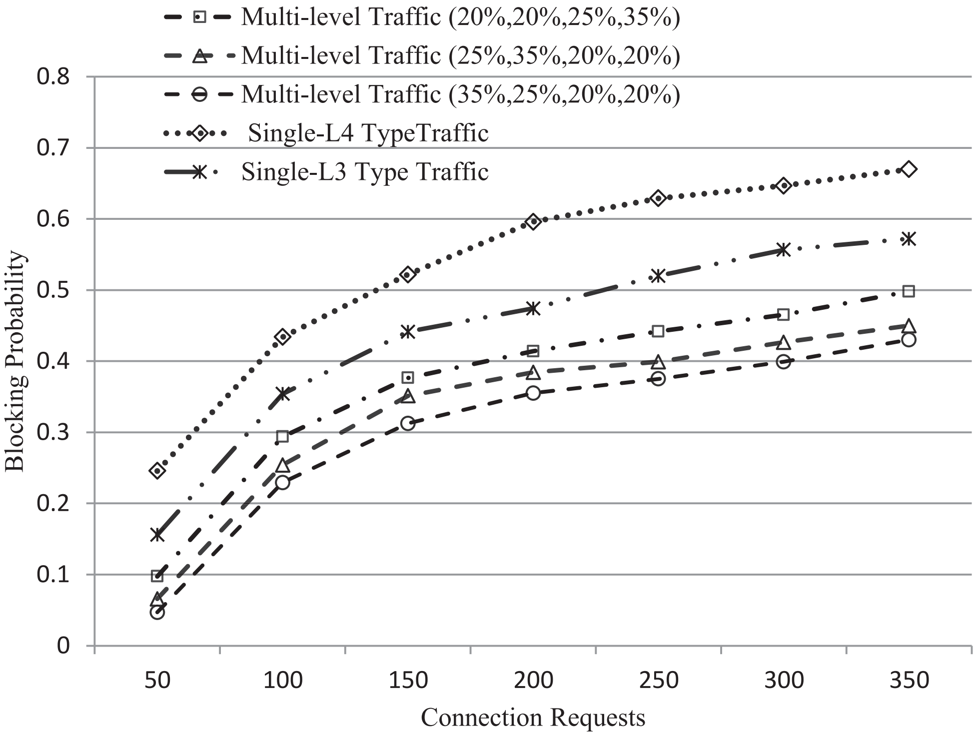


Figure 2.21: Blocking Probability Performance

scheme with varying traffic contributions with the scenarios in which all traffic will be of same nature and type of service requirements as per the scenario of L3 and L4 type. In Figure 2.21 the overall blocking probability of multi-level traffic categories implying all level has been evaluated and compared with with respect to scenarios having either total L3 type of traffic or total L4 type of traffic in the network. The simulation graph shows that in case of hybrid multilevel of traffic, the network performance has always been better than both of the cases carrying single type of either L3 or L4 type traffics. Further, it can be also observed that in case of the hybrid level of traffic, the variation of L1 and L2 percentage of traffic varies the blocking performance.

It can be further observed that the blocking probability of the scheme having only L4 level of all the traffic has highest blocking probabailty as compared to the case with only L3 level of traffic in the network. The higher blocking probability in case of L4 type of traffic is due to the stringent backup path consideration of the dual link failure vulnerability while in case of L3 type of traffic only single link failure has been considered. Categorized mixed traffic levels in the network requires different type and level of protection, thus, resources are utilized effectively as per the users service level aggrements for services.

We have also attempted to evaluate the resource utilization performance for the proposed and other compared cases. We have computed the performance of multilevel traffic scheme in terms of resource utilization ratio in comparison to the uncategorized traffic type in which each request is either of level L4 traffic or level L3 traffic type only in Figure 2.22.

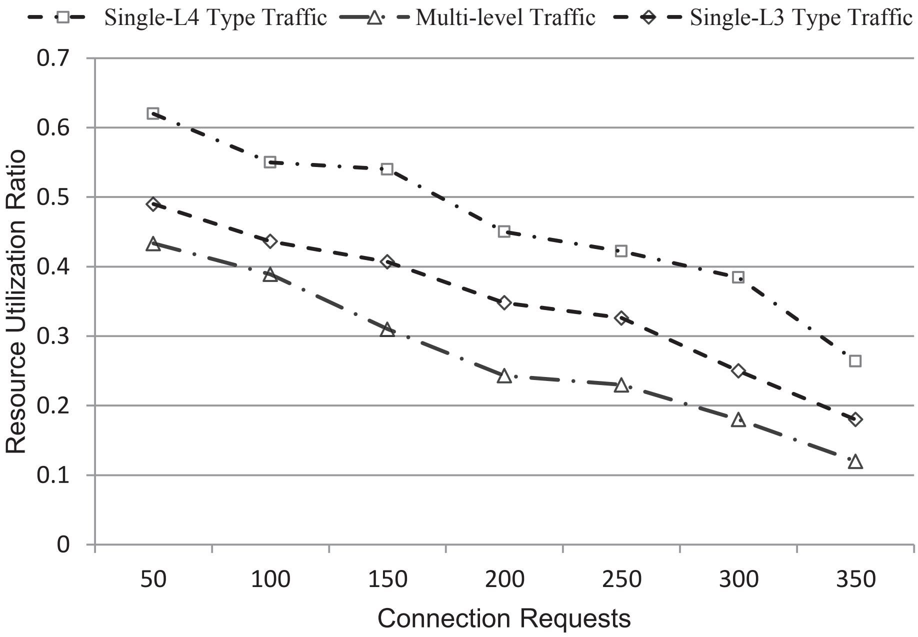


Figure 2.22: Resource Utilization Performance

It is observed from the plot that resource utilization ratio of multi-level categories of traffic scheme has smaller value in comparison to other two approach. Thus, it has better resource utilization ratio. It is seen from the graph that resource utilization performance degrades for all the compared cases as the connection requests increases in the network. A smaller resource utilization ratio means that the categorized traffic scenario establishes the connection requests by considering lesser network resources. Reasons for this may be is that traffic is categorized into different level as per the service requirement of distict user which makes the resources utilization more effective. Thus, resource utilization performance of the proposed scheme is superior than the approach in which all traffic is provisioned to same type of services.

In the recent past [Vizcáıno2016][Vizcáıno2013], four level of multicategory traffic has been investigated to compute lighpath considering the associated energy and spectral perspective for the network planning strategy with differentiated resiliency to elastic optical networks. In the present thesis we have studied the multi-categorised traffic to understand the blocking and resource performance behavior in survivable WDM networks. Further, we have also considered the same multi-categories of four level of traffic profile [Vizcáıno2013] [Vizcáıno2016] and simulated the same along with our proposed categorized one to evaluate the relative performance. The simulation result of the cases is presented in Figure 2.23. It is observed from the graph that our multicategorized profile performs better in general, because in our case services are shared type while in the reference case the categorization considers a mixture of dedicated, shared and unprotected categorization.

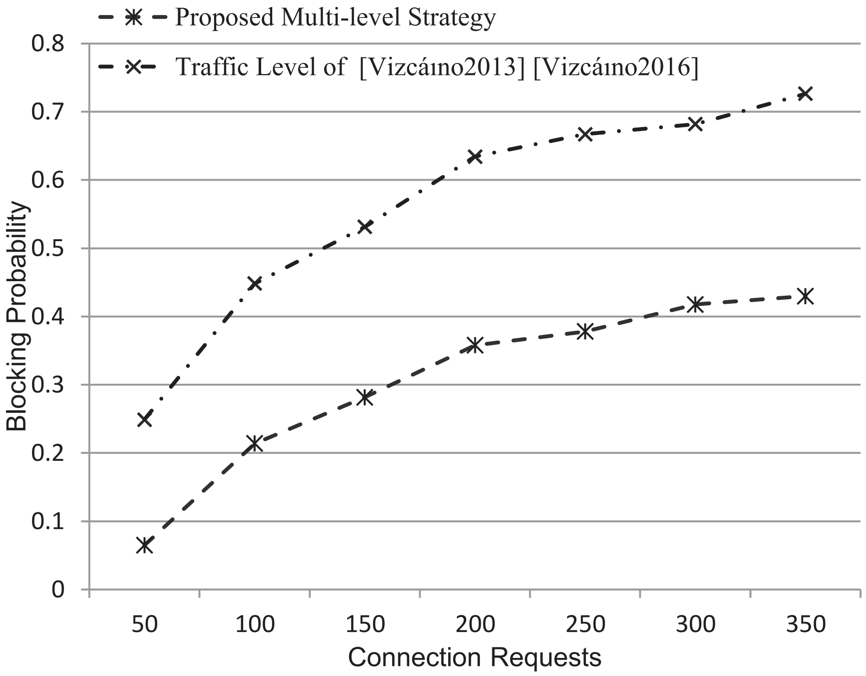


Figure 2.23: Comparative Blocking Performance

In conclusion, we observe that the use of categories of traffic at different level significantly improves the network performance compared to a network in which all traffic has same type and nature.

2.6 Summary

This chapter proposes an integrated hybrid mechanism for survivable fault tolerance in WDM networks for dynamic traffic. The proposed algorithm has been developed to exploit the benefits of both the conventional protection and restoration strategy to enhance the survivability performance of WDM networks. In the proposed strategy, at the time of arrival of connection requests, a primary working lightpath and a set of possible proactive backup protection path are identified. This strategy greatly reduces the overhead caused by discovering restoration routes dynamically after the failure.This plan further increases the network capacity by allowing backup path to assign channel bandwidths after the occurrence of failure. The network performance parameter in terms of blocking probability, increased accepted call (IAC), improvement in blocking probability (BPI) and restoration probability for the two distinct topologies have been simulated and evaluated for the varying number of lightpaths. It has been observed that the proposed hybrid strategy has always been superior to the dynamic restoration strategy. However it is not competitive with the pre-planned case. These strategies have been further tested for the restoration probability analyses and it has been observed that the proposed strategy supercedes to the pre-planned case also. It may be concluded with the findings of the simulation studies made in this chapter that for survivability in WDM networks considering all the performance parameters, the proposed hybrid approach emerges as a better choice.

When fault occurs, restoration bandwidth is allocated dynamically to one of these readily available pre provisioned backup paths to restore the disrupted lightpath traffic. Backup routes are readily available during the restoration process due to multiple precomputed routes preprovisioned in routing table. Thus, it can improve the setup and recovery process in the proposed hybrid mechanism as compared to dynamic restoration scheme. The results obtained from extensive simulation over the two different representative network topologies reveal that the proposed mechanism can reduce significantly the blocking probability and also has significant improvement in restoration probability.

Thus, the proposed hybrid survivability approach provides an improvement in the network performance for only a single type of services. However, in the network the requirements of the users may not be of same nature and therefore, the network has to cater different type and levels of services. Thus, we have proposed a heuristic scheme of hybrid nature and it's analytical model to handle multi-level of traffic in a survivable WDM optical network. The proposed strategy has been analyzed and simulated to evaluate the performance of multi-level hybrid traffic strategy in different combination of traffic scenarios. The simulation studied confirms the superiority of multilevel traffic in terms of blocking performance and also shows improved resource utilization. The findings of the chapters may, thus, be useful to predict the network performance in case single level of traffic as well as of multilevel service provisionings in a survivable WDM networks.

CHAPTER - 3

Survivable WDM Networks: Path Length, Resource and Energy based Routing

Internet service disruption occurs in the Wavelength Division Multiplexing (WDM) optical networks and this causes a huge data loss. In such networks, efficient routing failure solutions are very much required for data retransmissions, to ensure data delivery within specified delay frame. For the networks with connection requests arriving one after the other independently, it is important to develop a suite of interoperable strategies. This can solve for a link disjoint working primary and protection path pair upon the current network link state with sufficient capacity efficiency. Thus, the key challenge of routing and wavelength assignment problem is to determine efficient primary and backup paths for survivable optical WDM networks. Solving the routing problem optimally can maximize the total number of connection request accepted in the network; minimize blocking probability and resource utilization of the network. The study of proposed routing strategy includes three Survivable Routing and Wavelength Assignment (SRWA) heuristic approaches that select the route for survivable wavelength optical WDM networks. The heuristic routing approaches determine the primary and backup lightpath pair based on the different combination of path length. Thus, the proposed survivable routing heuristic strategy incorporates the influence of route length to measure the effect on the network's blocking performance in WDM network. However, the various rapidly growing services such as video-conferencing, IPTV, multimedia applications etc. are bandwidth thirsty nature and consume huge energy. Also the energy consumptions expected to grow in near future rapidly due to drastically increased Internet users and legion new services that are readily available to the end users. Energy consumed by network equipment’s contributes significantly in the overall energy consumptions worldwide. Thus, reduction in energy consumption is concerned issue; perspective to both the technologies and mechanism used in the design and operation of communication networks. Hence, in last subsection of the chapter a resource and energy aware scheme has also proposed to reduce the energy saving along with improved network blocking performance in a survivable optical network.

3.1 Related Work

With the development and extensive usage of WDM technology in optical network, the increased demand of bandwidth requirements of Internet users have been resolved. Nowadays, the optical networks based on WDM have enormous bandwidth capacity of a fiber, which involves several non-overlapping wavelength channels, carrying independent data. In all optical networks end users uses a single wavelength along each routing path over its lifetime to communicate with each other via all optical channels. Such paths are known as lightpaths and fact of using one common wavelength per path is known as wavelength continuity constraint. These wavelength channels create lightpaths, which are used to establish point-to-point optical connections that may span over several fiber links without using routers. For a given set of lightpath connection requests arriving dynamically to the nodes, the problem of determining the best route and assigning a free wavelength channel to each connection request is known as Routing and Wavelength Assignment problem. Thus, in WDM networks provisioning of lightpaths involve not only routing, but also the wavelength assignment which is NP-complete. Solving the routing problem optimally is computationally intractable [Chlamtac1996] because large number of feasible solutions exist. Algorithms of RWA problem generally fall into either static or dynamic categories based on their traffic assumptions. Dynamic RWA algorithms are more complex than static algorithms. A variety of RWA approaches and their performances have been extensively studied [Zang2000] [Randhawa2010].

The failure of fiber links or components may lead to loss for many users and large traffic blocked. Due to the tremendous amount of data transported, the network's ability to reconfigure and reestablish communication upon failure is indispensable in WDM networks [Zhang2004] [Grover2003]. In protection routing scheme, each incoming connection request is served with a primary path and a link disjoint backup path at setup time. In reactive restoration-based schemes, an alternate path is determined only after the failure occurs. In [Guo2006] author considered the survivable routing provisioning problem for single-link failure in which some primary path and backup paths are allowed to share a common resource to save resources and primary and backup path can multiplex the wavelength channels to enhance the network performance. Given a set of lightpath connection requests, the problem of setting up link disjoint primary and backup lightpaths for each arriving connection request is known as Survivable Routing and Wavelength Assignment (SRWA) problem [Beshir2009]. If lightpaths cannot be setup for a connection request then it is to be considered as blocked. Thus, to improve the performance of WDM networks a well designed SRWA algorithm is very important. The SRWA problem with wavelength continuity constraint is computationally intractable problem. In practice lightpath connection requests arrive over time without any knowledge of future arriving requests and the decision to accept or reject a lightpath request is made in real time. SRWA algorithm objective is to maximize the total number of accepted lightpath request or to minimize the total blocking probability of the overall network. The problem of SRWA is critically important to improve the fault tolerance capability of a wavelength routed all optical networks. The challenge in survivable optical networks is to devise route selection strategies to determine efficient primary and backup path pairs such that the network throughput performance is maximized while resource consumption is minimized.

With survivable routing, working and protection path pairs are link and/or node disjoint, in which two types of protection are defined: dedicated protection, and shared protection. The difference between the two lies in whether or not resource sharing of spare capacity is allowed between different protection paths. Survivable routing problem can be solved in two different ways, one way is to first determine the primary working path and then compute edge disjoint path as backup path using shared risk link group (SRLG) information of primary path known as separate path selection approach. Another approach is called joint path selection approach in which both primary and backup path selected in such a ways so that the combined cost is optimized [He2003] [Sivakumar2007].

Different type of link cost metric can be considered during the route selection process to compute lightpaths are available free wavelengths, common available wavelength, hop count, link's availability or reliability, holding time, number of converters etc. [Bhide2001] [Wen2005]. The main purpose of use of these metric in routing is to achieve an improved load distribution and/or to minimize the use of resources of the network for overall improved network performance. Authors of [Chaves2010] have used a link cost function of the fiber length and the availability of wavelength and these cost components have been adjusted to provide information of the network impairments. [Sen2001] proposed a way of choosing primary and backup paths so that length of both the path is shorter. Sen et.al. proposed one-step approach as the approximation solution and proved that the problem of finding such a pair of paths is NP-complete. Routing techniques are proposed by researcher in which they attempt to optimize the use of resources during the determination of routes through ILP formulation [Ho2004]. In [Ho2004], author has been considered link cost and explored the maximum extent of resource sharing for a protection path in finding pair of disjoint routes iteratively inspecting k-shortest paths until certain optimal path pair has been achieved invoking two-step approach by Dijkstra's shortest path algorithm. In [He2003] basic link cost and resource has been used to find pairs of link disjoint paths by selecting the primary path as the shortest such that path pair cost is minimum. In [Sivakumar2007] to minimize the combined cost of the primary and the backup paths, authors have been considered the integrated route cost as link load, hop length, mean load and variance of load for each route. Routes whose combined cost is minimum are then selected. It has been compared with hop count, least loaded and conversion free (minimize the use of converters in the primary path) approaches. An attempt has also been made by [Xin2001] to optimize the resource utilization by minimizing the overall combined cost of the primary and backup path, which has been selected from pre-computed K candidate route pairs.

However, there are various metric of network that has been used in the literature to estimate the cost of route in the establishment of connection requests. In order to obtain the maximum network performance and reduced blocking performance, the algorithm should consider the use of one or more of these network parameters. The motivation behind this present work is that the sole path length information may be incorporated for route selection to study the influence of route length on the network blocking performance in survivable routing.

3.2 Network System Model Assumptions

A wavelength routed WDM network is represented as a connected network graph G (N,E,W) such that the network has N nodes and E edges i.e. fiber links and W wavelength channels. The links are physical fibers connecting the nodes. Each link's bandwidth is partitioned into W wavelengths, which is used as communication channel. Each fiber link carries the same number of wavelengths. Nodes are not equipped with wavelength conversion capabilities. Connection requests are arriving at nodes independently and dynamically in the network. Source and destination nodes are randomly chosen from the set of N nodes. A lightpath request is equally likely to have any pair of network nodes as its source and destination. Each connection request between a source and destination pair arrives in the network randomly. A connection request is served by setting up a lightpath. The bandwidth requirement of each arriving connection request is equal to one wavelength channel capacity and it is occupied by the request until it terminates.

Notations:

Following notations are used to represent the objective function:

$s \in N$: Source node

$d \in N$: Destination node

W : Total number of wavelengths on each link

$w \in W$: Available wavelengths on each link

$l \in L \subset E$: Network fiber link

$r \in R_{sd}$: Set of candidate lightpath requests between node s and node d

$t_{s,d}$: Input traffic of requested connections between node s to node d

C_l : Cost of links represented by physical length of link or a hop distance.

Ψ^{r}_{w} : Flow indicator variable of lightpath r over w

Φ_l : Flow value on link *l*, which is expressed in terms of light path flows traversing link *l*

Lightpath flow indicator variable (Ψ^{r}_{w}) of lightpath r over *w* given as

$$\Psi^{r}_{w} = \begin{cases} 1, & \text{if lightpath r uses wavelength } w \\ 0, & \text{otherwise} \end{cases} \tag{3.1}$$

Total flow value on link *l*, expressed in terms of light path flows traversing link *l* as:

$$\Phi_l = \sum_{r|l \in r} \sum_{w \in W} \Psi^{r}_{w} \tag{3.2}$$

where, all such lightpaths are considered such that lighpath r traverses link *l,* i.e. all such lightpaths which cross the link.

3.2.1 Objective Function

The objective is to minimize the traffic demand of each link which can be specified as

$$Minimize \sum_{l \in L} C_l \, \Phi_l \tag{3.3}$$

Constraints:

Objective is subject to the following set of constraints:

- Same wavelength *w* is not assigned to the two lightpaths which traverse the same fiber link *l*

$$\sum_{r|l \in r} \Psi^{r}_{w} \leq 1 \text{ for all } w \in W, \; r \in R_{s,d} \tag{3.4}$$

- Input traffic demand of each *s-d* pair to be satisfied by the resulting lightpath flows

$$\sum_{w} \sum_{r \in \mathrm{R}_{s,d}} \Psi_{w}^{r} = \mathrm{t}_{s,d} \text{ for all } sd \text{ pair} \tag{3.5}$$

- Flow indicator variable can take either value 0 or value 1 only i.e.

$$\Psi_{w}^{r} \in \{0,1\} \quad \text{for all } r \in \mathrm{R}_{s,d}, w \in W$$

- The basic link cost is custom-designed, and can either be a constant (e.g., simply 1 for each hop), or can take dynamic network parameter into consideration (e.g., wavelength along link).

$$\mathrm{C}_{l} = 1, \quad \text{for all fiber link } l \in \mathrm{L} \tag{3.6}$$

- Basic cost of link can takes value as 1 for all links, which specifies the hop distance of fiber.

The above objective function minimizes the congestion and lightpath length of the established connection request. For better network performance lower congested links have to be preferable than the links which may be totally congested.

3.3 Survivable Protection Routing Heuristic Strategy

The proposed survivable routing uses three strategies for establishing an optimal primary route and a link disjoint protection path based on the different combinations of path length. The proposed routing strategies are simulated and their relative performance has evaluated. These strategies are designed to provide protection against any single link failure. Heuristic strategies used for survivable routing and wavelength assignment are Shortest Path Pair (SPP), Shortest Longest Path Pair (SLPP) and Longest Shortest Path Pair (LSPP) routing strategy. The suggested heuristic strategies described below differ from each other with respect to the path length in the selection of primary and backup path. In the process of computing primary and backup path using above described strategy, we prefer to select the links that have available free resources to avoid unbalanced state due to quick depletion of resources of link. In all the three strategies, the algorithm tries to assign an available free wavelength to the primary path using first fit algorithm. However, for the backup paths, the usage of shared protection wavelengths has been considered for wavelength assignment. The sharing of wavelengths between backup paths enhances the network's resource utilization.

3.3.1 Shortest Path Pair (SPP) Strategy

For each potential incoming traffic demand between the source node s and destination node d, this strategy computes a minimum path length route amongst the available routes. The selected minimum path length route is used as primary lightpath that is selected form the available feasible paths. For survivable routing, another route is determined as backup path which is link disjoint to the selected primary lightpath. The selected backup path is minimum path length from the available feasible disjoint paths of the selected primary lighpath. Here, both the primary and backup lightpath of a connection request are link disjoint and shortest in terms of path length. Description of the strategy has shown in Figure 3.1.

```
Input: Graph G (V, E,W), Where V = {$v_1$, $v_2$, .….$v_n$}set of vertices,
       Edges E = {$e_1$, $e_2$,…..$e_m$} and wavelengths W={$w_{1,}$ $w_2$, ..……. $w_w$}
Output: Wavelength continuous pair of shortest disjoint paths (in
        terms of hop length) for a connection request r between $v_s$
        to $v_d$, if available. Otherwise, connection request is not
        satisfied and blocked.
For each potential incoming connection request r at source vertex
$v_s$ for destination vertex $v_d$.
   1.Route selection:
      For each connection request r using Dijkstras routing
      algorithm determine the shortest path in terms of length to
      use as the primary path. After than set cost of all links
      infinity along the shortest primary path.
      Once again employs Dijkstras algorithm to find another
      shortest path to use as the backup path of connection
      request.
   2.Wavelength Assignment:
      2.1 Assign to primary path an available free wavelength
          channel using First-Fit algorithm. If no free channel is
          available connection request is blocked and discarded
          from network.
      2.2 When Primary path has been assigned successfully a
          wavelength channel, after than try to assign an available
          free wavelength to backup path by applying the concept of
          backup multiplexing of channel sharing among the
          different backup paths. If channel can be assigned,
          connection request accepted; otherwise, connection
          request is blocked and the channels assigned to primary
          path are released.
```

Figure 3.1: Description of SPP-SRWA Strategy

3.3.2 Shortest Longest Path Pair (SLPP) Strategy

In this strategy, shortest length path is used as a primary lightpath, if there is a free wavelength channel available across all the links of path. After deciding the primary path for the request, longest path which is link disjoint to the primary path is determined for backup path. Here, the primary path is the shortest one and backup path is the longest one in terms of path length. Selection of longest backup path can ensure that the shortest routes are to be available for primary lightpath. Description of the strategy has shown in Figure 3.2.

3.3.3 Longest Shortest Path Pair (LSPP) Strategy

This strategy computes a longest hop length path among the available paths between a given source s to destination d as the primary lightpath. This lightpath is established over a common free wavelength channel available across all the links of path. After primary lightpath computed, find a link disjoint backup path. The selected backup path is the shortest path. In this strategy, the primary path has the longest length while the backup path is the shortest one. This strategy has been used for comparative analysis. Description of strategy has shown in Figure 3.3.

```
Input: Graph G (V, E,W) Where V = {$v_1$, $v_2$, ..…….$v_n$}set of vertices,
       Edges E = {$e_1$, $e_2$,…..$e_m$} and W={$w_1$, $w_2$, ..……. $w_w$}wavelengths
Output: Wavelength continuous pair of shortest and longest path (in
        terms of length) for a connection request r between $v_s$ to
        $v_d$, if available. Otherwise, connection request is not
        satisfied and is blocked.
For each potential connection request r at source vertex $v_s$ for
destination vertex $v_d$.
   1.Route selection:
     For each connection request r using Dijkstras routing
     algorithm determine the shortest path in terms of length to
     use as the primary path. After that cost of all links of
     primary path set to infinity and find all feasible K paths by
     applying alternate routing concepts. From this set of K paths,
     choose a path which has longest length as backup path of the
     connection request.
   2.Wavelength Assignment:
     2.1 Assign to primary path an available free wavelength
         channel using First-Fit algorithm. If no free channel is
         available connection request is blocked and discarded from
         network.
     2.2 When Primary path has been assigned a wavelength channel
         successfully, after than assign an available wavelength to
         backup path by applying the concept of wavelength channel
         sharing among backup paths. If channel can be assigned to
         it, connection request accepted; otherwise, connection
         request is blocked and the channels assigned to primary
         path are freed.
```

Figure 3.2: Description of SLPP- SRWA Strategy

```
Input: Graph G (V, E,W), Where V = {$v_1$, $v_2$, ..…….$v_n$} set of
       vertices, E = {$e_1$, $e_2$,…..$e_m$} and W={$w_1$, $w_2$, ..……. $w_w$}
Output: Wavelength continuous pair of longest and shortest path (in
        terms of length) for a connection request r between $v_s$ to
        $v_d$, if available. Otherwise, connection request is not
        satisfied and will be blocked.
For each potential connection request r at vertex $v_s$ for destination
```

```
vertex $v_d$
   1.Route selection:
     For each connection request r, find all feasible K paths by
     applying alternate routing concepts. From this set of K paths,
     choose a path which has longest length as primary path. After
     then change the cost of all links of primary path to infinity.
     Apply Dijkstras routing algorithm again to determine a shortest
     path which is used as the backup path.
   2.Wavelength Assignment:
     2.1 Assign a wavelength channel to Primary path using First-Fit
         algorithm. If no free channel is available connection
         request is blocked. If a free channel is not assigned to
         primary path, connection request is blocked and discarded
         from network.
     2.2 When Primary path has been assigned free channel, try to
         assign an available wavelength to backup path applying the
         concept of wavelength channel sharing among the different
         backup paths. If channel can be assigned to it, connection
         request has accepted; otherwise, connection request is
         blocked and the channels assigned to primary path are
         released.
```

Figure 3.3: Description of LSPP- SRWA Strategy

3.3.4 Effect of Path Length on Survivable RWA

In preconfigured path protection scheme a primary path and backup path for every connection request is computed to cope up with a single link failure. Wavelengths assigned to backup paths can be shared to backup path of the primary path of a connection request in order to maximize the network resource utilization. In this strategy of sharing of backup resources, already reserved channels of backup lightpaths are preferred to assign to the backup paths and more free channels are available for the requirements of incoming primary paths.

Resources along with the protection paths are shared. Therefore, the switching nodes along the protection paths are not configured during the connection setup. Instead, upon the failure of any link of a primary path, the source node of failed primary path receives a failure intimation message from the source node of the link that has failed. Primary paths are always pre-provisioned with an alternate backup path. Hence after getting the failure notification message, the source node of the primary path initiates the setup process along the backup path to configure and enable optical cross-connect switches. After receiving the confirmation notification from destination node back to the source node, the interrupted traffic is restored over the backup path successfully. This process of restoration of failed traffic over backup paths involves various types of delays as described below:

D_f : Delay of detection of failure of the link

$D_{prop:}$ Propagation delay

D_{proc}: At each node processing delay

D_{oxc} : Delay of the setup of optical cross connect switches at every node

Therefore, overall cumulative delay (D), connotes in transferring traffic to backup lightpath in a situation of disruption of primary lightpath traffic due to failure of link can be expressed as follow:

$$D = D_f + (l'_{pn} - 1) * D_{prop} + D_{proc} * l'_{pn} + 2(l^b * D_{prop}) + 2(l^b + 1) D_{proc} + (l^b + 1) D_{oxc's} \quad (3.7)$$

where, l'_{pn} is number of node from failed link to source node of primary lightpath and l^b is hop length of backup path. Here queuing delay has not been considered as the circuit switched WDM network is assumed to have no optical buffers.

The overall total delay (equation 3.7) incurred to restore traffic due to failure depends significantly on the length of the primary and backup lightpaths. For the lesser delay of switching the traffic to restore affected connection, path lengths of l'_{pn} and l^b is required to be shorter as much as possible. This ensures the delay in the recovery of traffic to be smaller. Hence, faster recovery can be ensured, after an occurrence of the failure and it also affects the capacity cost efficiency besides the recovery efficiency. Sometimes this delay may be unacceptably high in case length of backup lightpath becomes very large. Such larger delay can be critical in a quality of service constrained WDM networks. Therefore, always shorter physical length of primary path and backup path is desirable. Sometimes a longer backup path may be considerable but longer primary path can never be preferable in survivable WDM network for improved performance.

3.4 Simulation and Performance Analysis

We have simulated the performance of the proposed heuristic strategy on two test network topologies as shown in Figure 3.4 and Figure 3.5. In the simulation model, each of the nodes in the network is capable to generate lightpath request to a random destination node. The sample USIP backbone network topology consists of 24 nodes and 43 links and the other sample US network topology has 15 nodes and 26 links, which have been commonly used by researchers. Each link is assumed to have the same number of wavelength channels. Each link in the USIP network topology of Figure 3.4 has considered W=10, i.e. 10 wavelengths. For US network topology each link has assumed W=8 wavelengths. We tested for dynamic traffic and compared the consequence of path length on network performance of survivable routing in single link failure scenario, where the primary path and protection path are established for each incoming connection request. It is assumed in the simulation that connection request arrives in a random way for a source-destination combination. In each of the simulation run, large number of requests has been generated and results have been averaged over twenty five simulation runs for performance measurement. If a connection request cannot be fulfilled due to limited network resource or route cannot be determined using described strategy, such connection requests are assumed to be dropped. Network performance has been measured on the three scenarios i) changing the network topology ii) lightpath load and iii) total wavelengths channels available. For performance analysis, we have considered the blocking probability (BP), number of Increased Accepted Calls (IAC) and Call Blocking Probability Improvement (BPI) performance metrics. The three heuristic strategies described in Section 3 have been evaluated on the two considered network topologies to decide the best option. However, in literature Joint Path Pair (JPP) selection strategy has been used to resolve the path selection problems. In the present analysis we study the proposed heuristics along with the JPP strategy for the comparative analysis. The JPP approach tries to find multiple pairs of candidate working and backup paths. Then the pair with the minimum cost sum is selected and may consume more resource with relatively higher complexity. The Joint Path Pair selection strategy is described as follow:

```
Compute K candidate $P_i$ primary routes with Pi representing the $i^{th}$ $(1 \le i \le K)$ primary route
For $P_i$, $1 \le i \le K$
    Compute an edge-disjoint route, represented as $B_i$
Find j such that $Cost(P_j) + Cost(B_j) = minimum(Cost(P_i) + Cost(B_i))$, $1 \le i \le K$
Select $P_j$ as the working path and $B_j$ as the protection path.
```

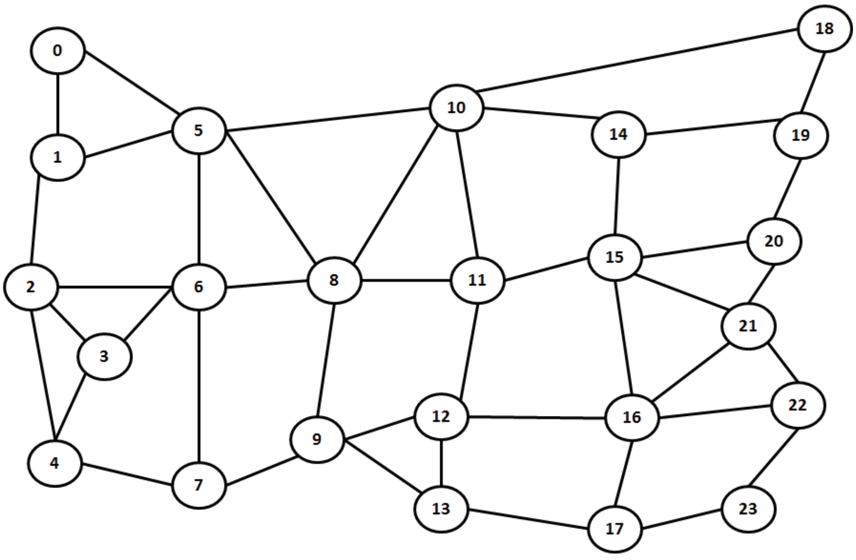


Figure 3.4: USIP Network Topology [Venkatesh2007]

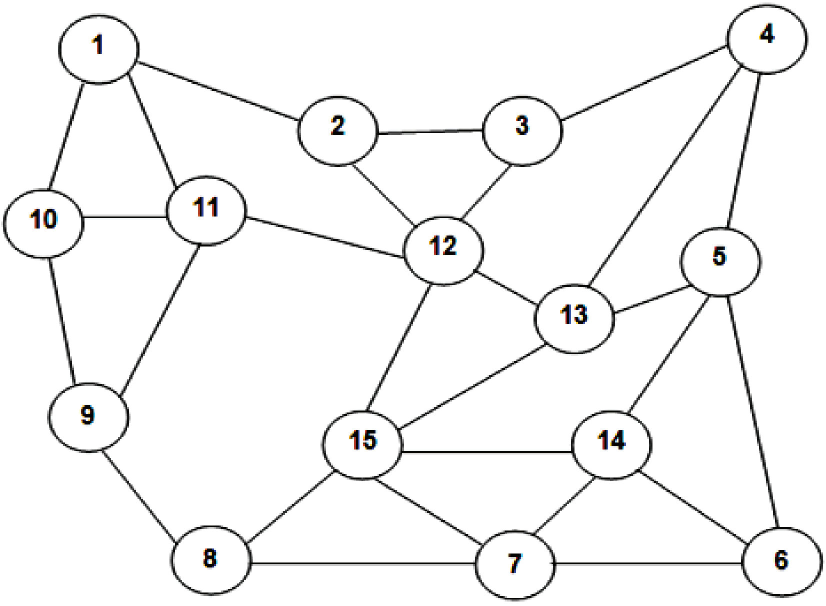


Figure 3.5: US Network Topology [Wang2008]

3.4.1 Analysis of Blocking Probability Performance

The call blocking probability performance of all the four routing strategies have been evaluated for different arrival rate of lightpath requests on the two standard network topologies and also compared with joint path pair strategy. In Figure 3.6 call blocking probability performance as a function of incoming connection requests has been simulated on the USIP network topology. In Figure 3.7, the comparative blocking performance of the considered strategies on the US network topology has been depicted. It is observed from both the graphs that SPP routing strategy give the lowest blocking probability as compared to the SLPP and LSPP routing strategy. Graphs show that LSPP strategy gives highest blocking performance than the SPP and SLPP strategy. Thus, as expected, results confirm that the strategy with a choice of longer primary or backup lightp shows a poorer network performance. The performance gets enhanced with the choice of relatively shorter primary or backup paths. This behavior can be attributed to the fact that longest path occupies more resource as compared to shortest path. Obviously, longest path leaves less channel resources for the subsequent arriving lightpath requests. On the contrary, shortest path consumes lesser amount of resources and leaves more resource for the incoming lightpath requests. It is also observed from the result that JPP strategy has lower blocking probability as compared to all the three heuristic strategies.

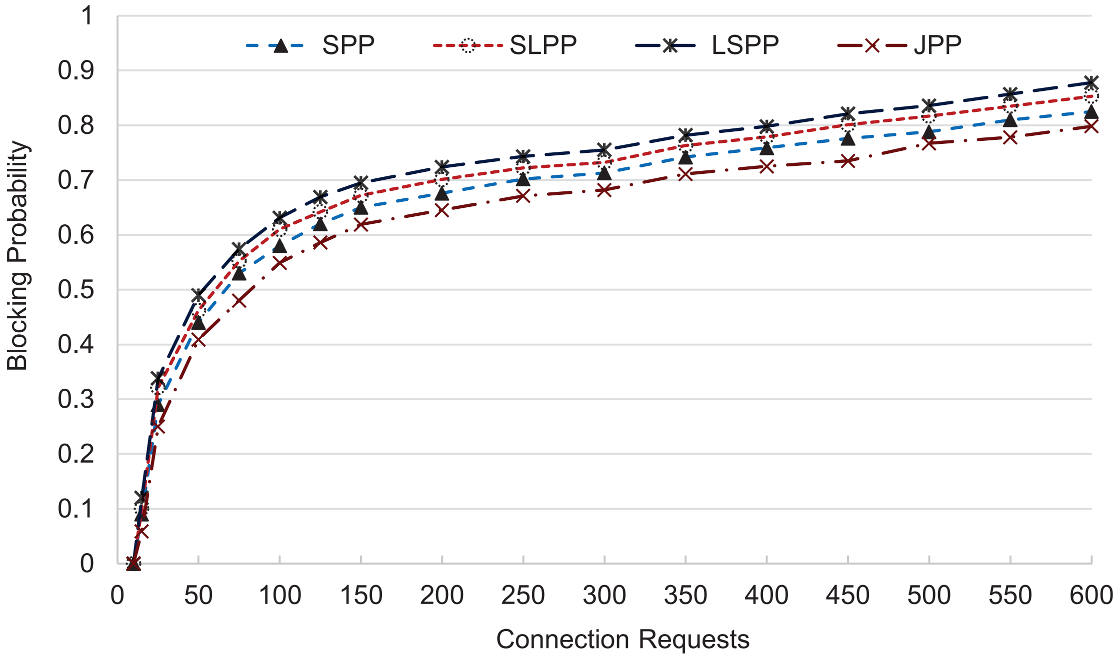


Figure 3.6: Blocking Probability on USIP Network Topology

However, it is noted that the JPP strategy shows even better performance for higher connection requests. This may be attributed to a larger resource utilization and algorithmic complexity. Further for a lower connection request the additional benefits vanishes and the proposed heuristics are preferable choice. This analysis infers that for a lower to moderate traffic the proposed heuristics can be better choice with less complex implementation.

It is found from the figures that at higher traffic rate blocking probability performance of all three strategies increases because of the availability of less quantity of network resource. It can also be observed from the graphs that SLPP performs better than LSPP in terms of blocking probability. The reason is that, SLPP assigns longest path to backup path and backup path may use a wavelength that may be sharable amongst other backup paths. Performance of SPP strategy surpasses the performance of SLPP and LSPP strategies in choosing routes for lightpath protection for WDM network. Further the JPP strategy involve the combined shortest path considering both the primary and backup path pair and thereby shows a relatively lower blocking probability at higher traffic. This improvement requires a compromise over the network path selection constraint involving both the primary and backup paths. The present work employs on the simpler network path selection strategies to achieve satisfactory performance with a simpler path selection heuristic approach.

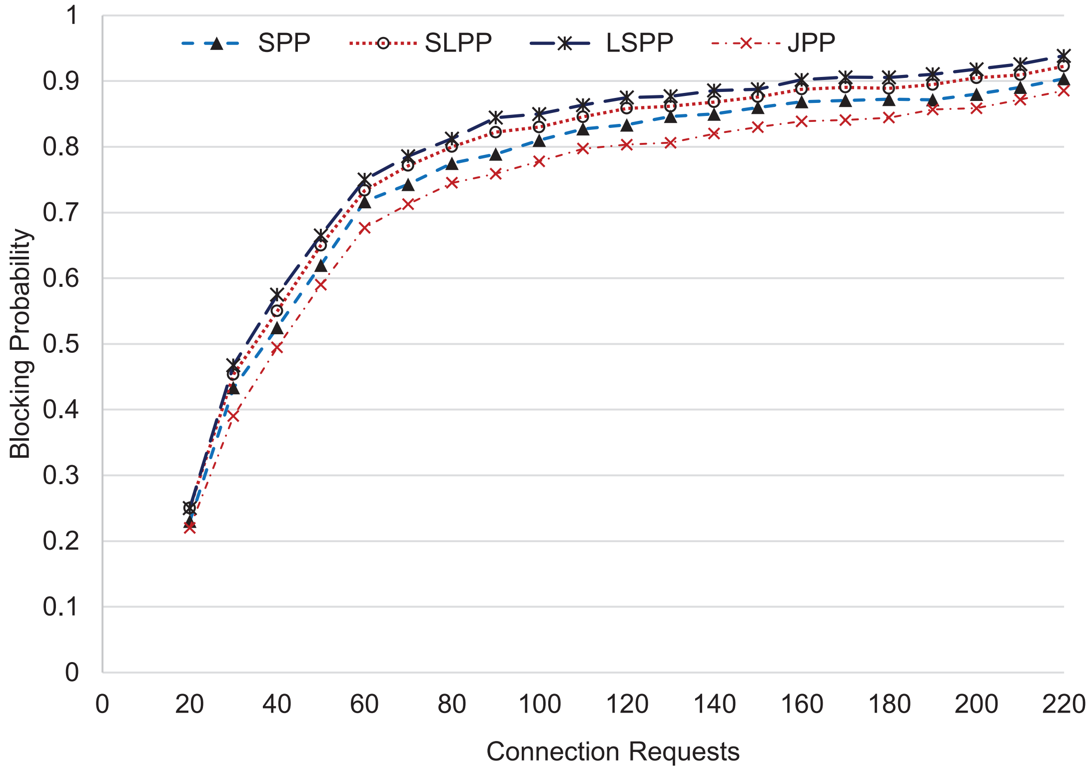


Figure 3.7: Blocking probability on US Network Topology

Further, the proposed heuristics have been tested by varying the resource of the network in terms of increase the number of available wavelength. In graphs of Figure 3.8 and Figure 3.9 call blocking performance with respect to different number of wavelengths per fiber are presented. The number of lightpath requests considered for USIP network topology is 600 requests and for US network topology, considered number of requests is 300. Figure 3.8 shows the blocking performance over the USIP network topology of

Figure 3.4 and Figure 3.9 depicts the changes in call blocking performance over US network topology of Figure 3.5 for all the three routing strategies.

Graph shows that blocking probability reduces when number of wavelengths per fiber link increases in both the network topologies. Blocking probability of LSPP strategy is highest amongst the three strategies. It is observed that as the number of wavelength channels per link increases, the call blocking probability is reduced for all strategies in both the topologies. Blocking probability of SPP strategy is lower than other two strategies, which evidences the superiority of the SPP strategy. The results reveal that better network performance can be achieved when abundant resources are available in the network.

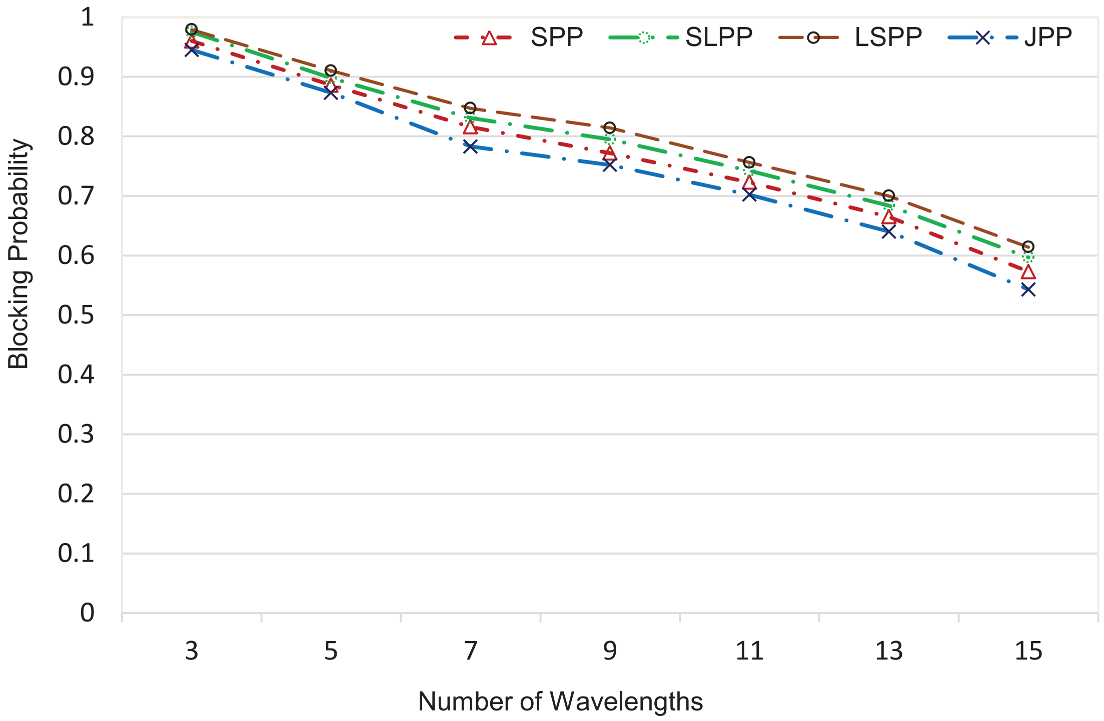


Figure 3.8: Blocking Probability vs Number of Wavelengths on USIP Network Topology

3.4.2 Analysis of Number of Increased Accepted Call Performance

Routing performance of a network is also characterized by number of increased accepted call (IAC) performance (as defined in equation 2.16) to express the relative performance of considered algorithm with respect to the superior strategy. Since among heuristic approaches, the SPP has emerged a better one, so we have considered IAC performance of SLPP and LSPP with respect to SPP and the same has been plotted in Figure 3.10 and

Figure 3.11 for USIP and US topology. However, joint path selection mechanism (JPP) performs even better than SPP, thus IAC performance parameter defines the relative superiority of JPP with respect to SPP and this performance parameter has also been plotted in both the figures to visualize the increased call acceptance behavior of all the attempted strategies. Each link in the USIP network topology of Figure 3.4 has considered W=10, i.e. 10 wavelengths. For US network topology each link has assumed W=8 wavelengths.

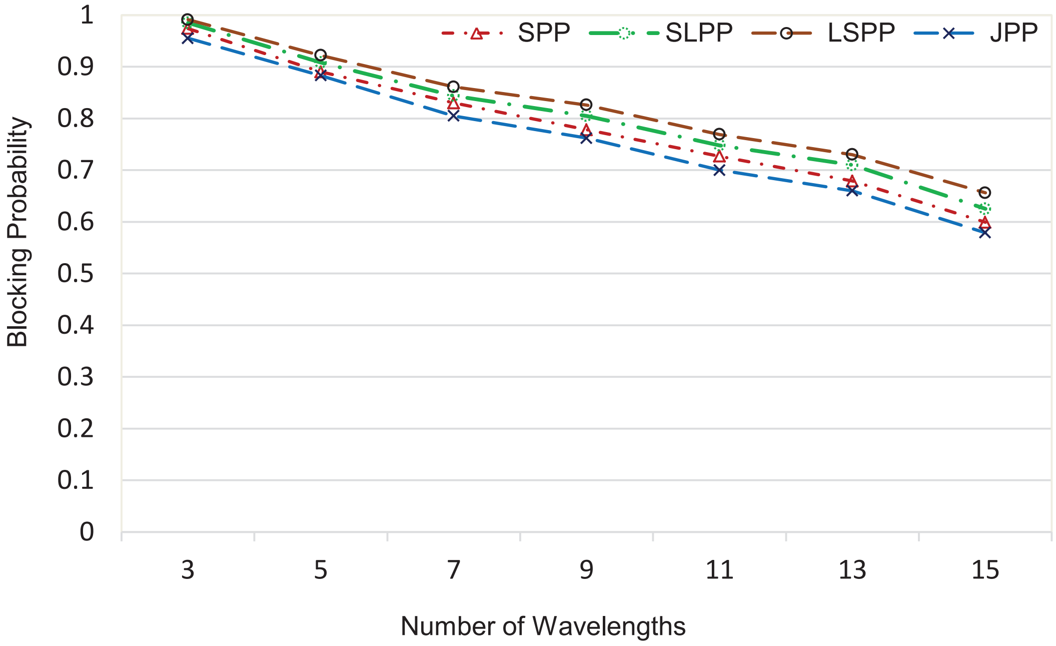


Figure 3.9: Blocking Performance vs Number of Wavelengths on US Network Topology

It is observed from the Figure 3.10 that SPP has a better call acceptance with respect to both the SLPP and LSPP and this improvement becomes further distinct as the traffic increases. It may also be noted that SPP improves at faster rate in case of LSPP than the SLPP case. However, the JPP claims a higher acceptance performance with respect to SPP and increases with the increase in the traffic. This may be attributed to the lower call blocking performance of the JPP over the SPP. This performance parameter in the case of US topology have also been simulated and the findings have been plotted in Figure 3.11.

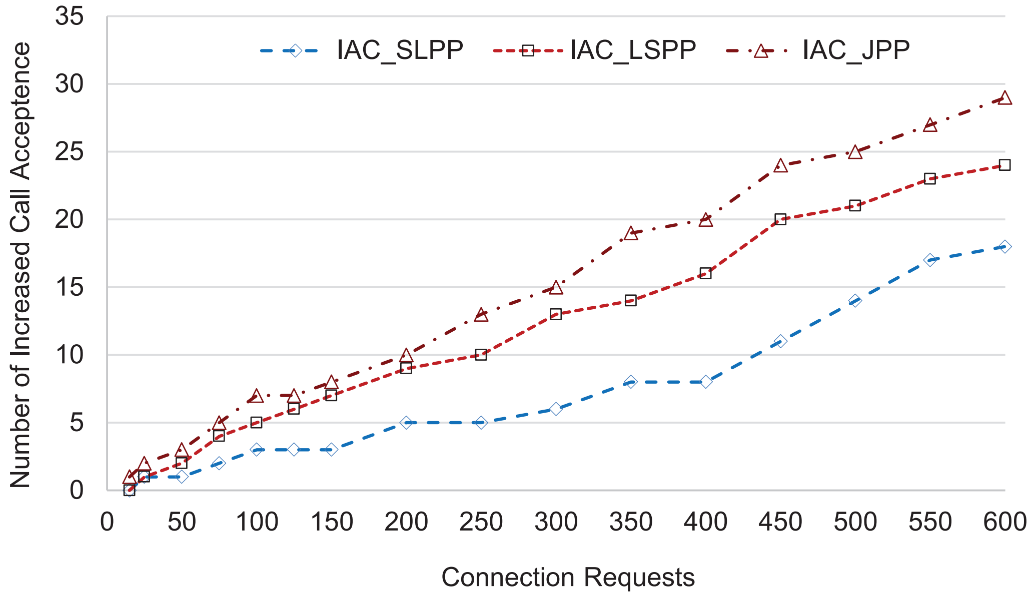


Figure 3.10: Increased Accepted Call Performance on USIP Topology

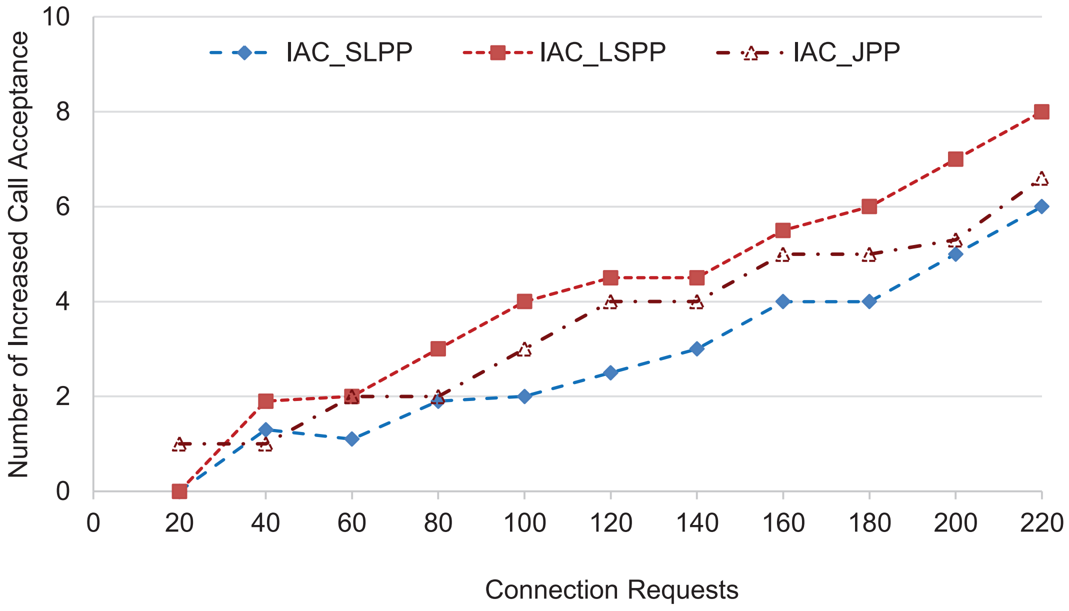


Figure 3.11: Increased Accepted Call performance on US Topology

It is observed that the qualitative behavior of the measured IAC for all the cases are similar but with a quantitative difference. In these cases the rate of change of IAC depends on the network resource and volume of arriving lightpath traffic. The numeral difference and rate of change of IAC on both topologies is due to lower average nodal degree, number of node and link of US network topology as compared to USIP topology.

3.4.3 Analysis of Improvement of Blocking Probability Performance

Figure 3.12 and Figure 3.13 shows the call blocking probability improvement of SPP strategy with respect to SLPP and LSPP over the two considered network topologies. For USIP network topology we have considered W=10 and in US network topology each link has assumed W=8 wavelengths. This performance parameter for the case of JPP has also been evaluated with respect to SPP to make the analysis more informative. Percentage improvement of blocking probability of SPP is better compared to SLPP and LSPP strategy on both the network topologies. The result shows that SPP can improve blocking performance more significantly compared to SLPP and LSPP strategy. In Figure 3.12, percentage improvement of blocking probability of SPP strategy is 3% to 9 % approximately against SLPP strategy and approximately 4% to 11% against LSPP over network topology. The similar analysis of SPP, SLPP, LSPP and JPP approach has also been carried out for US network topology and the findings have been presented in

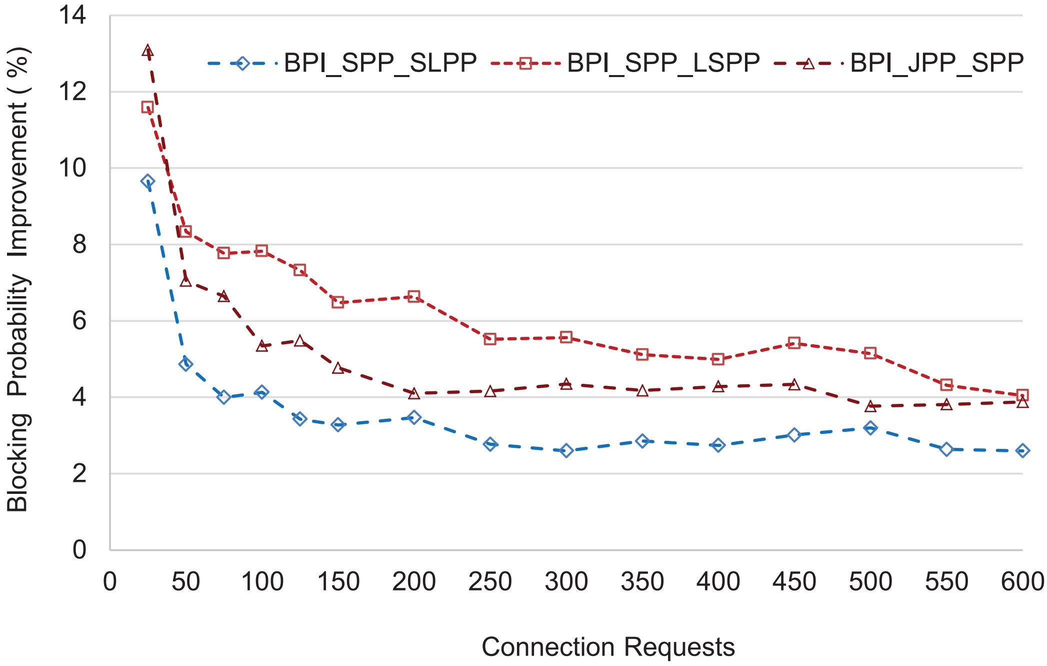


Figure 3.12: Blocking Probability Improvement Performance on USIP Topology

Figure 3.13. Blocking performance improvement of SPP strategy against SLPP is 2% to 4% and SPP can improve blocking probability 3% to 9% against LSPP strategy. It is evident from the result that JPP strategy performs better than SPP strategy. Graphs show that at higher incoming lightpath request, percentage improvement of blocking

probability decreases. Reason for this is that at high incoming lightpath traffic, blocking probability increases as depicts by all strategy, therefore, blocking probability improvement does not increases significantly. At the higher arrival rate of incoming connection requests, the blocking performance benefits of SPP routing strategy is significant and does not decrease comparatively to other SLPP and LSPP strategy. It may be inferred from the preceding discussion that the length of route has a significant role in deciding the performance of the routing strategy in case of survivable WDM networks.

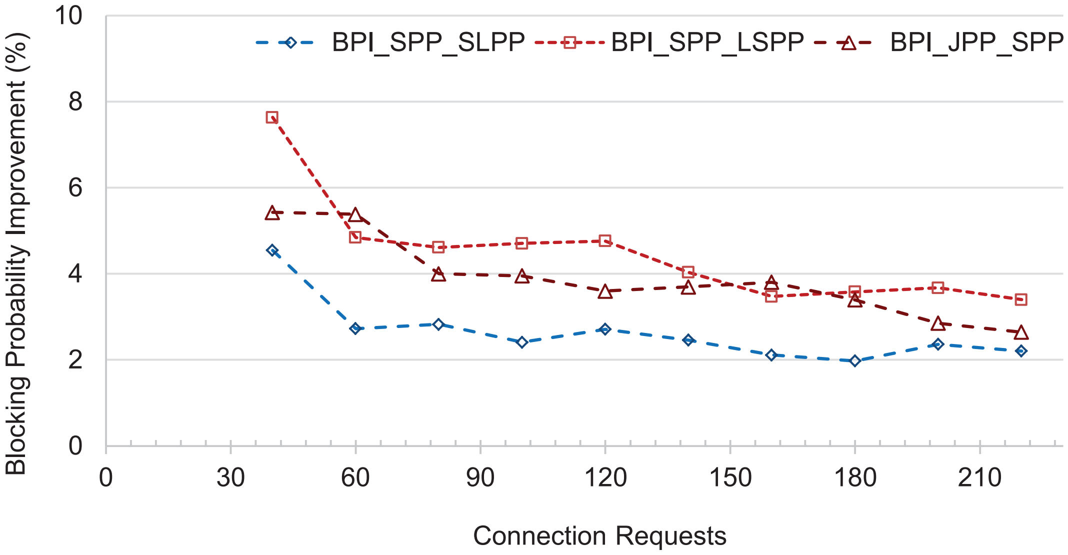


Figure 3.13: Blocking Probability Improvement Performance on US Topology

The study reveals that the shorter path length selection strategy is most preferable among the heuristics approach, however joint route selection strategy also performs best at higher traffic. It has been observed that for lower to moderate traffic this benefit may not desirable due to additional complexity. Further for the desired QoS, shorter paths are required as it enhance the reliability and reduces the delay in the networks.

3.5 Resource and Energy Aware Survivable Routing

Wavelength Division Multiplexed based optical network is employed as backbone network that supports exponential requirement of huge bandwidth demands. In future, fiber deployment in WDM optical networks can be used to deploy fiber to home services will ramp up. The various rapidly growing services such as video-conferencing, IPTV, multimedia applications etc. are bandwidth thirsty nature and consume huge energy. These power energy consumptions in telecommunication networks causing an environmental issue concern to the global warming, green infrastructure and adverse environmental impact. Also the energy consumptions expected to grow in near future rapidly due to drastically increased Internet users and legion new services that are readily available to the end users [Vereecken2011]. Energy consumed by network equipment's contributes significantly in the overall energy consumptions worldwide. Thus, reduction in energy consumption is concerned issue; perspective to both the technologies and mechanism used in the design and operation of communication networks. Thus, one of the challenging aims for the future of information and communication technologies is reduction of the energy consumption [Aleksic2009].

WDM carries tremendous volume of information and play a key role in supporting the next generation application services in the future. In this way any fiber link failure may cause the loss of connections that carry an enormous amount of information. Resiliency can be achieved by re-routing the affected traffic to spare protection resources. However, when we consider survivability in network, the energy consumption may increase due to extra resources which may be provisioned to handle failures depending on the type of resiliency provisioned. Survivable protection routing with energy saving has been considered in this section such that network throughput will not compromise at the cost of energy saving which is consumed in the network.

In literature, different mechanisms have been studied to reduce the energy consumption in wavelength routed optical and wired network [Heddeghem2010] [Vizcáıno2016] [Zhang2010] [Jirattigalachote2011] [Coiro2011a] [Constantine2014]. These mechanisms are based on the concept to minimize the energy at the time of lightpath provisioning or at the time of network design process. A model for the energy consumption of practical networking devices in terms of cost and energy perspective has been suggested in [Tucker2009]. In [Wu2009] authors had proposed heuristic algorithms to solve the power aware RWA problem in a scenario of static traffic model. Authors have minimized the nodes and fibers used to route the lightpaths. In [Heddeghem2010] authors estimated power consumption for packet switching techniques of optical-electrical-optical convertor (OEO) based link-to-link traffic grooming and end-to-end grooming scenario. An integer linear programming formulation has been suggested in [Jirattigalachote2011] for the power efficient dedicated path protection in which reserved backup resources can be set to sleep mode to reduce the energy consumption of components in WDM optical network. Sleep mode represents a low-power, inactive state from which devices can be suddenly waken-up upon the occurrence of a triggering event, e.g., a failure detection [Monti2011]. Thus, support of a sleep state option need to be available in most of the devices. In [Coiro2011b] RWA problem has been solved to improve power efficiency through leaving unused optical fibers in a dynamic traffic scenario to minimize the active amplifiers in multi-fiber optical network. Most considerable techniques follow to turn off unused devices to reduce and save the energy drained by optical layer of WDM survivable networks. These approach performed by the use of a sleep mode option in the equipment. In [Hasan2010] traffic grooming has been attempted with energy perspective. Authors in [Vizcáıno2016] have provided the energy and spectral efficiency based differentiated quality of protection considering the protection switching time for heterogeneous service.

In [Cerutti2010] fiber links has put to sleep or off state depending upon a threshold value when the traffic increases in the GMPLS network. The purpose is to reduce the network wide energy consumption in a GMPLS network by rerouting the lighpaths. In [Bao2012] author proposed a power efficient heuristic in which the link cost and fiber cost has been used in the routing process in a multi-fiber network. The suggested shared path protection approach separates the working paths and backup paths into different fibers as much as possible. Thus, working wavelengths and the backup wavelengths are expected to be separated by different fibers. Due to packing of primary lightpaths toward the same fiber may create bottleneck of resources causing drop of traffic. Author did not consider the energy consumption of fiber link in the routing process. In case of survivability most of the components that has deployed for protection are unutilized most of the time, thus can be put to sleep mode and reactivated when required in the presence of failures. Thus, it is necessary to ensure that other performance parameters of the network should not be compromised. However, most of the approaches compromise network performance at the cost of minimizing only the energy consumption in the network. In this section we will propose a network resource and energy aware survivable protection strategy without compromising the network throughput performance.

3.5.1 System Network and Energy Model

We assume that optical WDM network is represented as G (N,L,W) where set of nodes is N, set of fiber links L and W is set of wavelengths in the network. It is assumed that wavelength conversion is not available in the network. An optical WDM network comprises of various components. A node consists of an optical control system which electronically controls the node. It has optical cross connect switching (OXC) system a optical node and a fiber link is used to connect two optical nodes. The data communication takes place physically through lightpath at the optical WDM layer. A typical optical link has shown below in Figure 3.14 [Kaabouch2012]. Thus, in WDM network links has been connected by Optical cross connects (OXC). The various other important components are pair of Multiplexer (MUX) and De Multiplexer (DMUX) for each line interface, Transponders and each network link is composed of a number of optical fibers; at two end of each fiber consists of pre and post Erbium Doped Fiber Amplifiers (EDFAs) and along it a number of In Line Amplifiers (ILAs) are deployed. Number of EDFA deployed on link depends on the length of the fiber. The energy consumption to establish a lightpath connection request is depends on the energy consumed by transponder, transceivers, OXCs, EDFAs, MUX and DMUX. Thus, energy consumed in a wavelength routed network is contributed by various components. Hence, total energy consumption is consists of the energy consumed by nodes and links in the route.

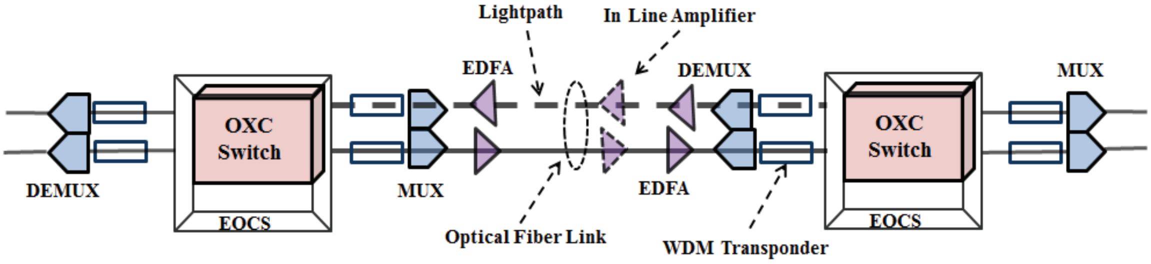


Figure 3.14: An Optical Link

Total energy consumption of a node i can be given as:

$$E(i)=E(eocs)+E(Trans)*\sum_{j\in T}\chi_j+E(\mathrm{p})*\mathrm{W} \tag{3.8}$$

here, $E(\mathrm{eocs})$ is energy consumed by operational electronic optical control system at a node, $E(\mathrm{Trans})$ is energy consumed by associated transponder, T is the number of transponders, $E(\mathrm{p})$ is energy absorbed by active input/output port pair and W is the wavelengths which are active. If transponder is active then χ_j=1 otherwise χ_j=0. Thus, total energy consumption over all the nodes is than the sum of all individual nodes energy consumptions.

At the two end of each fiber link between two nodes; pre and post EDFAs are placed and also there is a number of inline amplifiers (ILAs) are deployed along it. Normally, it is considered that each fiber link consists of several spans with 80 km length. The number of amplifiers used along the fiber link connecting node i and node j can be given as

$$\mathrm{ILA}_{ij} = \frac{\mathrm{Len}_{ij}}{\mathrm{d}_{\mathrm{ILA}}} \tag{3.9}$$

Here, Len_{ij} is physical distance between node i and node j, $\mathrm{d}_{\mathrm{ILA}}$ is the distance between two ILAs which is considered to be 80KM.

Total energy consumption of a link $l_{i,j}$ is given as:

$$E(l_{i,j}) = \mathrm{ILA}_{ij} * E(ILA)+E(Pre^{EDFA})+E(Post^{EDFA}) \tag{3.10}$$

Here, $E(ILA)$, $E(Pre^{EDFA})$, $E(Post^{EDFA})$ are the energy consumed by the ILA, pre and post amplifiers respectively. Thus, whenever a fiber is not used on a given link then the optical amplifiers along it can be assumed to be off and energy will be saved. Hence, total energy consumption across all the fiber links is than the sum of energy consumption of all individual links.

Thus, the total energy consumed by the network is represented as

$$E^{Total} = \sum_{n\in \mathrm{N}} E(n) + \sum_{l\in L} E(l_l) \tag{3.11}$$

Where, $E(n$ and $E(l)$ is the energy consumed by node and link respectively. When total energy consumption of the network is estimated, then only those link and node is considered which are in active state. In case of the backup lightpath, those node and link which belongs to backup may be set to sleep state mode. In sleep state, component consumes negligible or no energy. Thus, energy does not consumed by backup lighpath since it is not involved in the data communication before primary lighpath failure occurs.

3.5.2 Resource and Energy Aware Survivable Routing

Consider Figure 3.15 and Figure 3.16 and assume that each fiber has two wavelength channels. In case energy aware RWA is performed, the goal is to minimize the energy consumption in network. Consider four connection requests C_1, C_2, C_3 and C_4. Suppose that first a connection request $C_1(3,7)$ arrives, then the primary connection lightpath 3-6-7 is established as shown in Figure 3.15. Then, $C_2(1,5)$ connection reaches. This request is setup using path 1-3-6-7-5 through the links 3-6 and 6-7 to use the working resources of the already provisioned working primary lighpaths in the network. When connection request $C_3(2,5)$ arrives next, it will be routed through the path 2-7-5 to prefer the already provisioned working resources. When $C_4(5\text{-}7)$ connection request arrives, it is also try to setup path 5-7 considering energy aware rationale. Thus, $C_4(5\text{-}7)$ request is not established due to the exhaust of two available wavelength along route 5-7 and further no more spare resources are available. Thus, only three lighpaths have been established.

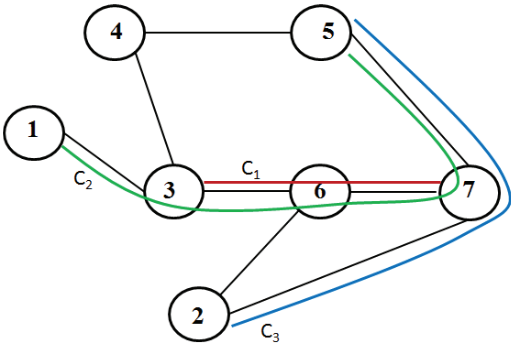


Figure 3.15: Energy Aware RWA

Consider the resource aware RWA scenario to route the above four connection request C_1, C_2, C_3 and C_4 as shown in Figure 3.16 using path 3-6-7, 1-3-4-5, 2-7-5 and 5-7 respectively. When request $C_1(3,7)$ arrives, then primary route is setup using path 3-6-7. Then, request $C_2(1,5)$ reaches and it is established the lightpath route 1-3-4-5 using links which have more available resources. When request $C_3(2,5)$ arrives is setup using 2-7-5 path due to available resource usage and balancing. If next incoming request $C_4(5,7)$ arrives, it can be setup using the route 5-7 due to same network resource aware rationale consideration. Hence, all four requests have been accommodated in the network. Thus, resource is properly utilized and network throughput has improved. Thus, performance of the network may degrade if only energy minimization will be the sole concern in routing due to the blocking of connection requests.

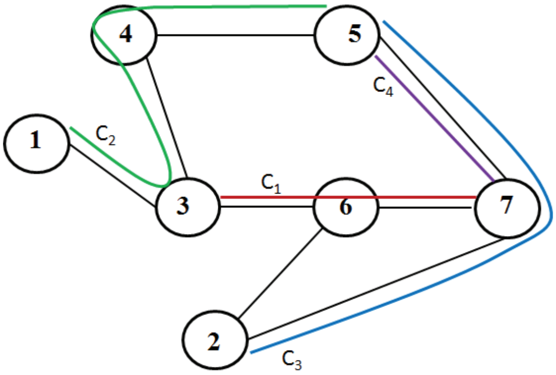


Figure 3.16: Resource Aware RWA

Now, consider the RWA problem for the case of survivable routing scenario in Figure 3.17 and Figure 3.18. Thus, each connection request is established using a pair of primary and backup route to support the survivable protection routing. Assume each fiber has two channels and two connection requests $C_1(3,7)$ and $C_2(1,5)$ in the network .

When request C_1 (3,7) arrives, then, using energy aware rationale, route 3-6-7 setup as primary path and route 3-4-5-7 setup as backup route. When next C_2(1,5) request arrives, it choose route 1-3-6-7-5 taking advantage of the links that use the already provisioned working resources in the network to minimize the energy. However, due to the consideration of energy minimization rationale, primary route of C_2 request has setup through link 1-3 and its disjoint backup route is not feasible, thus, C_2 request will not be established and is rejected.

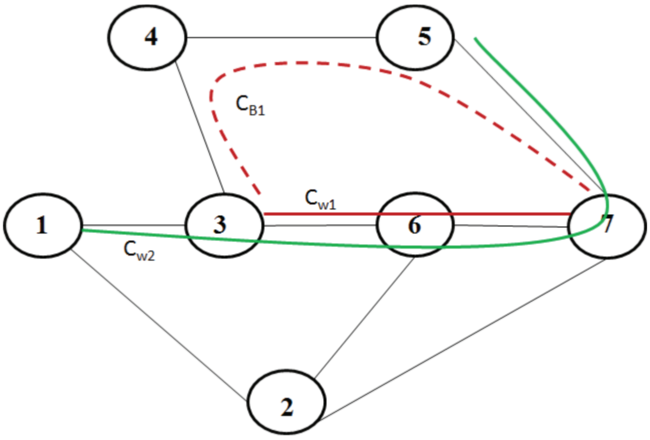


Figure 3.17: Energy Aware Survivable Routing

When we route both the request C_1(3,7) and C_2(1,5), considering the available network resource to balance the traffic load then both connection requests can be setup successfully in the network using lighpaths as shown in Figure 3.18. First connection request C_1(3,7) established using path 3-6-7 as primary lightpath and path 3-4-5-7 as backup lighpath. Finally, when connection request C_2(1,5) reaches is established using 1-2-7-5 and 1-3-4-5 as primary and backup lightpath respectively. Thus, both requests have been successfully established in the network.

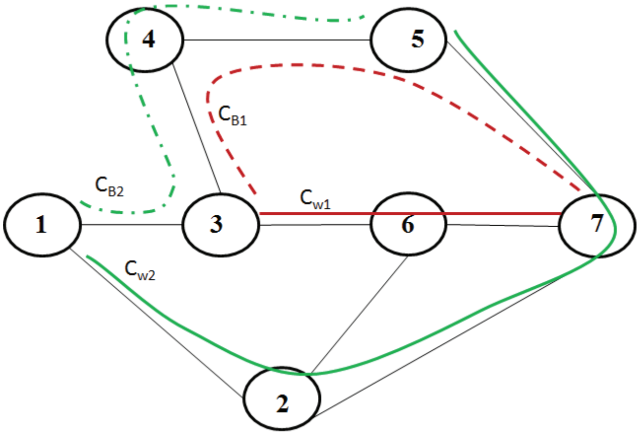


Figure 3.18: Resource Aware Survivable Routing

From the above examples, it has been observed that consideration of network resources in route selection process can establishes more number of lighpath connection requests in the network. Thus, when reducing the energy consumption is the only sole concern in RWA process may not give better network performance.

Hence, in our proposed approach, we consider both the network resources and energy parameters in the routing process so that the network blocking performance cannot deteriorate. The proposed scheme works as follows when a request between a source node and destination node arrives in the network; pair of routes is computed. The approach considers the resource availability and energy of the link in the network such that links which does not have wavelengths will be omitted from the network topology. The proposed survivable connection provisioning algorithm considers the wavelength resources of the link and energy usage among primary paths and secondary paths during the link cost assignment phase in the routing process.

Weight of links for Primary path Computation

Primary lightpath is chosen such that the weight of links along the primary path has more available free resources and has less energy consumption. The weight cost for each fiber link, $LC_p(i,j)$, for determining a primary route is as follows:

$$LC_{\mathrm{P}}(\mathrm{i},\mathrm{j}) = \begin{cases} \infty & \text{if } \mathrm{W_f} = 0 \\ \alpha E(l_{ij}) + (1-\alpha)\dfrac{\mathrm{W_t} - \mathrm{W_f} + 1}{\mathrm{W_t}} & \text{if } \mathrm{W_f} > 0 \end{cases} \tag{3.12}$$

Where, $E(l_{ij})$ is the consumed energy necessary to operate the link l, $\mathrm{W_f}$ and W_t are the free wavelength and total wavelength resources respectively. The weighting parameter α is set to highlight the relevance of energy over resources available. In simulation value of α = 0.3 has been assumed to give more importance to the network resources. Hence, for the uniform distribution of the network resources across all the links and less power necessary to operate amplifiers along the links will be preferred to traverse by primary paths. This weight factor is used to minimize the energy consumption of the network by balancing the resources in the network for incoming connection request.

Weight of links for Backup path Computation

For the backup protection path, wavelength assignment scheme to be used is such that it maximizes the usage of shared backup wavelength resource as much as possible to enhance the resource utilization of the network. Backup wavelength sharing strategy is used for the provisioning of wavelengths to the backup path under the wavelength continuity constraint. In this approach multiple backup paths may share a wavelength channel if their primary lightpaths are disjoints.

After the primary lightpath has been establishment, a link disjoint backup lightpath is setup to address the issue of the single link failure survivability. For the backup path to traverse those links that have assigned i.e. reserved more backup wavelength resources (i.e. $\mathrm{W_{bs}}$) and having less energy consumption is preferred. Thus, the weight of the link for backup path computation can be adjusted as follows:

$$LC_B(\mathrm{i},\mathrm{j}) = \begin{cases} \infty & \text{if } \mathrm{W_f} + \mathrm{W_{bs}} = 0 \ \ or \ (i,j) \in \mathrm{P} \\ \alpha E(l_{ij}) + (1-\alpha)\dfrac{\mathrm{W_t} - (\mathrm{W_f} + \mathrm{W_{bs}}) + 1}{\mathrm{W_t}} & \text{if } \mathrm{W_f} + \mathrm{W_{bs}} > 0 \end{cases} \tag{3.13}$$

where, $\mathrm{W_{bs}}$ is the already reserved backup wavelength.

3.5.2.1 Proposed Algorithm

A lightpath requests are purveyed all-optically for a source node to a destination node without going through any optical- electrical-optical conversion at intermediate nodes. Energy that a lightpath consumes to establish a working path is the energy consumed by nodes and links involved in the path. The total energy consumed in network is the sum of the energy consumed by all the requests provisioned in the network. The node and link component that belongs to the backup paths can be put to low power state i.e. into the sleep mode to save energy consumptions. The backup lightpath are not required to be active and usable always; thus, it can be put to idle state of sleep mode to save operational energy of the network.

The proposed resource and energy aware survivable routing strategy works as follows: For each arriving request a set of routes are computed using the current energy consumption and resource availability of the links. This process will determine the routes which have less energy consumptions and more available wavelength resources in the network so that the arriving traffic will be distributed in the network based on resource availability. This step will help to enhance the possibility of finding the resources to be assigned to the request successfully and balance the traffic load. Thereafter, among the computed routes such route is determined and chosen using another link weight cost for each link such that the primary lightpath is established using working resources of the already provisioned paths. The cost of links of primary path is set to a small constant in order to discourage the utilization of links with backup resources. Thus, the chosen path is shortest route among candidate routes with minimum energy. The detailed pseudo code of the proposed resource and energy aware survivable routing strategy is given as follows:

Algorithm 3.1: Resource and Energy Aware Survivable Routing Strategy

Inputs: Network information G(N,L,W), source node s and destination node d
Output: Pair of primary (PPath) and backup lighpath (BPath) or NULL if no solution available

```
Begin
 For(each incoming request R(s,d))
    KrouteSet ← ComputeK_shortestRoute (G, Source s, destination d)
     PP ← NULL,    E(PP)=∞
     While( KrouteSet $\neq \Phi$ )
       $P_i$ ← KrouteSet
       KrouteSet = KrouteSet- {$P_i$}
       Compute weight of each link in $P_i$ as
           $W(l_{i,j}) = \begin{cases} \delta * W_{primary} & \text{if } l_{i,j} \in \text{existing primary lightpath} \\ E(l_{i,j}) & \text{otherwise} \end{cases}$
       Compute energy weight of route $P_i$ as
           $E(P_i) = \sum_{l_{i,j} \in P_i} W(l_{i,j})$
       If ( $E(P_i)$ <E(PP) )
           Set PP ← $P_i$
     End_While
     if(PP $\notin$ NULL)
         PPath ← PP
         AssignWavelength(PPath)
     else  Block Connection request
    KrouteSet ← ComputeK_shortestRoute (G-{PPath}, source s, destination d)
     BP ← NULL
     E(BP)=∞
     While( KrouteSet $\neq \Phi$ )
       $B_i$ ← KrouteSet
       KrouteSet = KrouteSet- {$B_i$}
       Compute weight of each link in $B_i$ as
           $W(l_{i,j}) = \begin{cases} \delta * W_{Backup} & \text{if } l_{i,j} \in \text{existing backup lightpath} \\ E(l_{i,j}) & \text{otherwise} \end{cases}$
       Compute energy weight of route $B_i$ as
           $E(B_i) = \sum_{l_{i,j} \in P_i} W(l_{i,j})$
       If ( $E(B_i)$ <E(BP) )
           Set BP ← $B_i$
     End_While
     if(BP $\notin$ NULL)
         BPath ← BP
         AssignWavelength(BPath)
     else  Block Connection request
  End
```

Algorithm 3.2: Determine K Shortest Routes

Inputs: Network information G(N,L,W), source node s and destination node d
Output: set of K shortest route or NULL if no solution available

```
ComputeK_shortestRoute(G, source s, destination d)
 Begin
   route ←NULL
   routeKSet←NULL
    for (each arriving request R(s, d) )
           if (R(s,d) =Primary Path Request)
              Adjust cost of all links according to equation (3.12)
           else
              Adjust cost of all links according to equation (3.13)
            if_end
           shRoute←Dijkstra(G,L,W,s,d)
           routeKSet← routeKSet ∪ {shRoute}
           i←1
         while( i<K && routeKSet != NULL )
             path← routeKSet[p]
             routeSet=routeKSet - {path}
             route← route∪ {path}}
             while (path∉ NULL and i<K)
                 l←leastCostLink (path)
                  path=path- {l}
                 shRoute_next← Dijkstra(G-{l},L,W,s,d)
                 if (shRoute_next != NULL )
                     routeKSet← routeKSet ∪ { shRoute_next}
                     route←route∪{shRoute_next}
                      i←i+1
                   if_end
                 G← G ∪{l }
             end_While
        end_While
    end_for
  return routeKSet
end
```

3.5.3 Performance Results Analysis

In this section we evaluate the blocking probability and energy consumptions performance analysis of the proposed approach. A program has been written using java in which the algorithm is implemented to emulate the scenario of simulation model as described in previous chapter on Linux environment. It takes the topology information, wavelength information and random source and destination traffic. First fit and backup sharing wavelength assignment scheme has been implemented in the module to assign wavelengths to the primary and backup path respectively. We consider the NSFNET network topology as a network model having 22 Links and 14 Nodes [Nag2008] as shown in the Figure 3.19. Numbers on each link denote the length between nodes in kilometer. Each fiber has been partitioned into W=10 wavelength channels. The bandwidth requirement of each connection request is assumed to be one spare wavelength channel. It is considered that each fiber link consists of several spans with 80 km length and in-line optical amplifiers placed every 80 km. The considered value of energy consumed by various components (in watts) of the network is $E(\text{eocs})$=150W, $E(\text{Trans})$=50 W, $E(ILA)$=15W, $E(Pre^{EDFA})$=10W, $E(Post^{EDFA})$=20W and energy consumed by optical switching input/output port is 107 mW [Coiro2011a] [Heddeghem2010]. Source and destination node pairs of arriving lightpath requests are randomly distributed among the networks node.

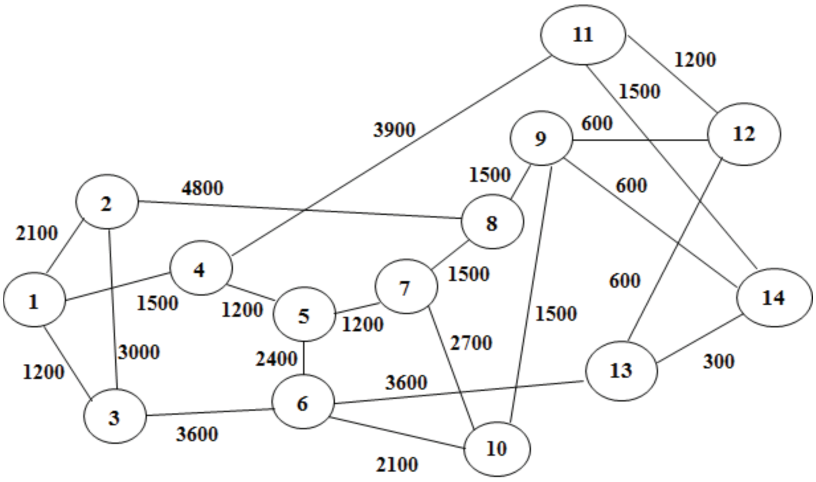


Figure 3.19: NSF Network Topology

Nodes do not have capabilities of wavelength conversion i.e. node does not equipped with any wavelength converters. Wavelengths are assigned to the primary path using the first fit assignment approach and backup wavelength sharing approach is used for the assignment of wavelength to the backup path. We consider dynamic traffic environment and assume that each connection requests arrive randomly with a random source and destination pair, one at a time and the connections which has established remains in the network for the duration of the experiment. Performance of proposed REA approach has compared with the i) Energy Aware (EA) approach: In this approach energy saving is only the major concern by using the resources that have already been provisioned as working resources and as much as possible use the links with existing lightpaths [Jirattigalachote2011]. ii) Energy unaware (EU) approach in which an adaptive shortest path algorithm is used to determine pair of primary and backup routes based on network resource. It is pure conventional routing scheme in which energy saving parameter is not considered at all [Jirattigalachote2011]. iii) Power aware shared (PAS) approach proposed in [Bao2012] is used to compare the proposed REA approach. In their approach working wavelengths and the backup wavelengths has separated by different fibers and do not consider the network resources and energy metric in route search process. Our proposed resource and energy aware (REA) protection approach instead of blocking the request due to non-availability of resources, another search for the possibility of primary lightpath setup is initiated. Thus, the chance of finding the available resource to candidate set widens and reduces the blocking probability.

Figure 3.20 shows the blocking probability performance over NSFNET network topology as a function of arriving connection requests for our proposed scheme along with the other existing strategies for the comparative analysis. In all the cases blocking probability increases with an increase in the arriving traffic requests. It has been observed that all the cases have similar qualitative behavior but with the quantitative difference.

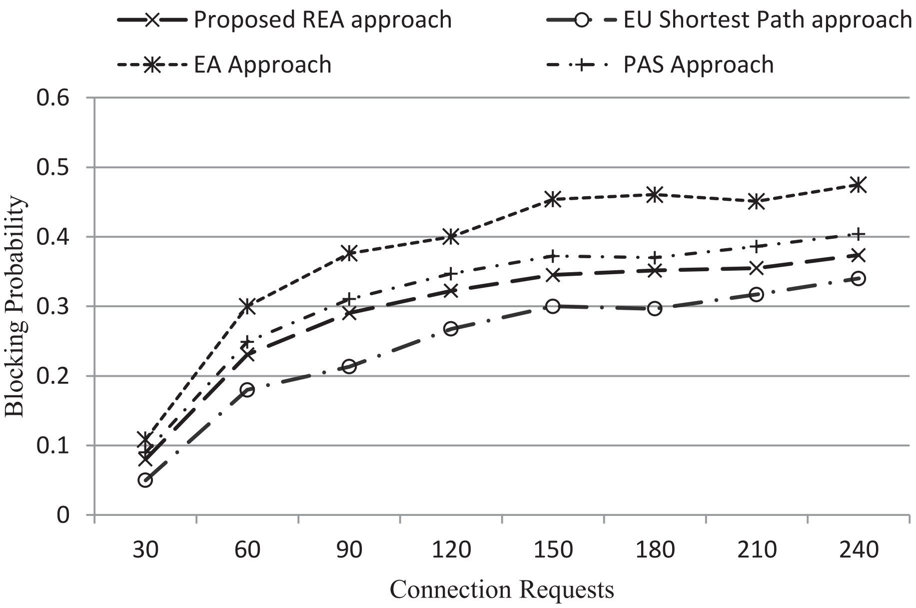


Figure 3.20: Blocking Probability Performance

It is noted that the blocking probability of the energy aware (EA) approach has the worst performance while the energy unaware (EU) shortest path routing approach has lowest blocking probability. It is attributed to the reason that energy aware approach only consider the energy saving and not consider the network resources efficiently. In in this case the chosen route can be longer and may encounter effectively more congestions.

However, in case of energy unaware adaptive shortest approach, routing process uses the available resource and path length in route computation.

It is observed that our proposed approach has better network performance as compared with the EA case, however, it underperforms with respect to the EU case owing to considered network resource and energy in the route selection process.

From the graph it is observed that at lower load traffic there is not significant difference in the performance, however, at higher load performance of REA approach in terms of blocking probability is better than PAS approach. It is attributed to the fact that REA approach considers usage of resources and energy saving in the route selection and due to the chance of finding available resource in the widen set of candidate routes. It has also observed that blocking probability of all the approaches increases with an increase in traffic load in the network. This is due to more requests arriving in the network and free resource capacities are not sufficiently available to accommodate the arriving request.

In Figure 3.21 we compare the total energy consumption of the EA approach, EU approach, PAS approach and proposed REA approach. Proposed REA approach performs better than energy unaware (EU) approach and power aware shared (PAS) approach. REA approach performs better at moderate load traffic but its performance is very close to PAS at low and high traffic load. REA approach has better performance due to the consideration of resource and energy factor into routing process. It is also observed that at high traffic load REA and PAS have no much significant performance

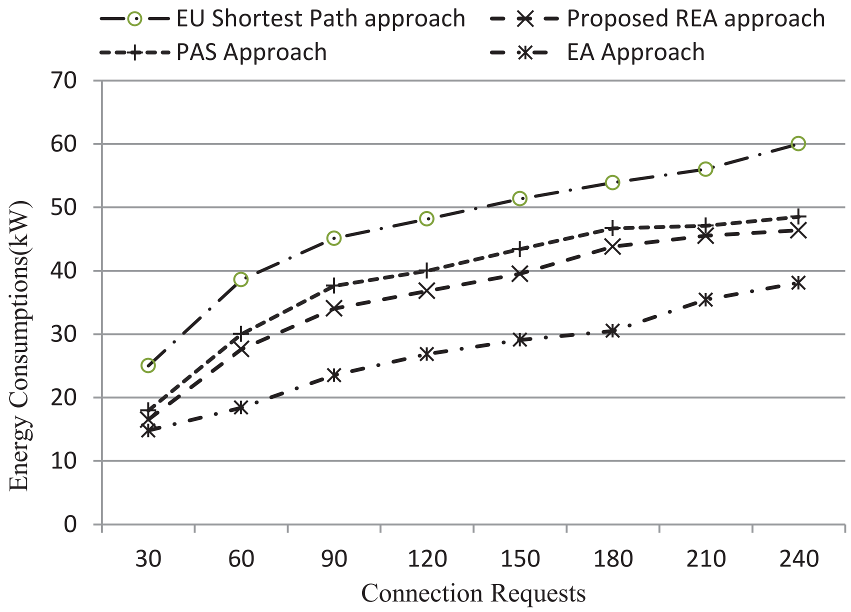


Figure 3.21: Energy Consumption vs Connection Requests

improvement because when large connection requests are in the network, more network resources will be utilized due to which incoming connections can’t be routed in links having primary lightpath due to unavailability of free wavelengths. Thus may be no more benefits in terms of energy saving. However, REA approach has low blocking probability compared to PAS and EU approach. Thus, for network performance in terms of low blocking probability proposed REA protection approach without consumption of high energy.

3.6 Summary

In this chapter three heuristic approaches have been proposed and evaluated for the survivable routing strategies in optical WDM networks. The proposed heuristic strategies use different path length combinations to select the primary and backup path for incoming connection requests. The routing strategies have been used to describe the influence of path length on the network performance in survivable WDM networks. The survivable protection routing strategies select the primary and backup protection path based on their length which further influences the blocking probability of the networks. These routing heuristic strategies have been simulated and analyzed for two different network topology by varying traffic load and wavelengths availability on a link. Results confirm that the SPP routing strategy performs better than the SLPP and LSPP routing strategies. The study has further been extended to include joint path pair strategy for routing solution in the survivable networks. This has been considered as a reference study to compare and infer the importance of the findings of the proposed heuristic strategies. It has been found that the proposed heuristics are simpler and showing very close performance with respect to JPP at higher incoming requests. These investigations mainly focus on route selection considering only path length and do not accounting the network resources and energy parameters of the network.

However, in WDM networks, the reduction of energy consumption either through technologies or by the mechanism and operation of the network management appears an important strategy. The last subsection of chapter focuses on resource and energy aware scheme to propose and analyze network performance. The performance has been simulated under the constraint of resource and energy metrics. The proposed algorithm shows superior blocking performance and energy consumption performance with respect to other compared strategies therein.

CHAPTER - 4

Resource Aware Multi-lightpath Routing in WDM Networks

The existing networks are interfaced with the Wavelength Division Multiplexing (WDM) based core networks to exploit the existing huge bandwidth with minimal delay. Wavelength routed WDM optical network enable the telecommunication and data networks to operate at extremely very high data rates. Thus, advancements of WDM technology is capable of satisfying the growing requirements of high bandwidth of next generation users and bandwidth intensive applications [Mukherjee2004]. The wavelength routed WDM networks carries many light beams of different wavelength, routed through a network switching fabric to support heavy data traffic to meet the required flexibility.

These high speed backbone transport networks are generally prone to component or links failure which causes a huge information loss. Therefore, a robust survivable WDM mesh network become an essential requirement for the acceptable reliability. Backbone network architectures are either partial or full mesh, thus, designing routing protocols to such a network becomes a complex problem [Chang2015]. Hence, in such cases more than one path has to be available in between any two nodes in the network. This multipath availability can be utilized to handle traffic requirement of the network efficiently and traffic can be distributed over these multiple paths.

In this chapter a wavelength resource aware multi-lightpath survivable routing strategy is proposed to improve the network performance and network congestion scenario. Generally, all routing and wavelength assignment algorithm solve the route selection and channel assignments problem separately. Proposed approach determines wavelength and the route simultaneously for an incoming lighpath connection request. It solves the route and wavelength channel assignment problem at the same time, jointly without dissociating the problem. The proposed survivable routing approach is capable of balancing network load and resources along with ensured protection through the wavelength continuity constraint in lightpath selections.

4.1 Related Work

In order to meet the traffic demand of existing and future communication applications, wavelength routed optical networks are considered to be a viable solution for next generation wide-area backbone networks. In such network, failure can cause huge data loss. Thus, survivable routing protocols are necessary for the data network. A routing approach is survivable if uninterrupted services can be guaranteed in case of a failure in the physical network. The problem of routing and wavelength assignment for a survivable network is most important for increasing the reliability of wavelength routed all optical networks. For survivable routing, requires two link-disjoint paths for each connection request so that when working path fails, its traffic can be rerouted to a link disjoint backup path. However, with the increase in the network size, the difference between the number of possible lightpaths and the lightpaths which could be established practically also increases. Once the paths have been identified, we need to route the traffic through such path and assign a wavelength to each of them. This is referred as the Routing and Wavelength Assignment problem of optical WDM networks [Zang2000]. The major goal of the solutions of RWA problem is to establish the maximum number of lightpaths under the availability constraint of wavelength channel in the optical fiber. Appropriate algorithm is not available to yield an exact optimal solution of the RWA problem in polynomial time. Hence, survivable RWA problem becomes NP complete. Hence, heuristics algorithms are necessary to solve the RWA problem. A number of heuristics have been proposed by researchers to obtain good solutions [Shen2001] [Keqin2008]. The RWA problem can be solved as two sub problems; one is route selection problem and another is wavelength assignment problem [Chlamtac1996]. These two sub problems of RWA, route selection and wavelength assignment can be solved in either way; first routes are selected and then the wavelengths are searched for assignment to the chosen route or first wavelengths are searched and then routes are selected. Alternatively, routes and wavelengths search can be considered jointly to implement RWA problem [Birman1995]. Generally, wavelength routed networks adhere to wavelength continuity constraint which can be relaxed by using wavelength conversion functionality either in full or partial way at few nodes in the network [Singh2004]. However, the complexity and huge cost of a wavelength convertible node makes this approach less attractive for network design.

The important routing algorithms considered in the literature are fixed routing, fixed-alternate routing and adaptive routing algorithms [Zang2000]. Fixed-alternate routing gives better call connection probability than fixed routing due to availability of choice of alternate routes in former one for establishing lightpath [Ramamurthy1998c]. Both of the algorithms do not capture network status information at run time as both are static by nature. So there is a need of such algorithms which can dynamically select the routes by incorporating current network status in the route selection process; like wavelength availability on each of the links in real time. Such algorithms is known as adaptive routing. The adaptive routing selects the route between source destination node pair dynamically at run time. Two different routes for a given source destination node pair can be selected at different course of time due to the changes in the network status in adaptive routing algorithm. In general, the adaptive routing approach gives a better call connection probability as compared to other two routing strategy. Most of the survivable routing algorithms may not always find all paths such as k-shortest path and may suffers from trap problem.

Mostly the routing protocols deployed in the Internet use a single path for traffic forwarding between each source destination node pair. However, sometimes multiple paths can be computed to select a single best path amongst them [Heand2008]. The multipath routing algorithms can satisfy user’s QoS requirements for applications without adding much to the existing infrastructure [Ruan2014]. The multipath routing helps in reducing the backup path requirement for high performance applications leading to superior network performance [Lin2006] [Rai2007]. The number of free wavelengths available on fiber link limits the number of end-to-end connections and also physical constraint such as wavelength channel spacing in a fiber, capability of optical transceivers, and bandwidth granularity affects the connection setup [Asuman2003]. Moreover, a light-path with the wavelength continuity constraint leads to inefficient utilization of wavelength channels and results in higher blocking probability [Kumar2002][Mohan2000]. The wavelength continuous paths is preferred over wavelength non-continuous paths due to the simplicity and lower cost of WDM node without wavelength conversion capability. Hence the performance of RWA solution for a network differs in terms of; whether wavelength conversion support is there or not, and also whether the support is partial or full [Mukherjee2004] [Singh2004].

Another type of heuristics for solving RWA problem works on link by link basis which selects the route based on the current status of the network. In this methods each link has been assigned a cost or weight, based on some network parameters like total free wavelengths, common free wavelength, total busy wavelengths, link availability, link delay etc. The various link weight based RWA heuristic algorithms have been proposed which consider the network status. The dynamic RWA algorithm proposed by [Mokhtar1998] adaptively chooses the path for a connection request which arrives randomly. This algorithm does not use any predefined path. One of the routing heuristic proposed in [Li1999] is based on the congestion status of the path. In this approach connection requests are sent towards the destination node over multiple paths parallelly. At the other end of the destination node one route with maximum number of free wavelengths is selected to setup lightpath which is a least congested path. But this approach has large setup delay and overhead. A distributive routing algorithm is discussed in [Dharma2004] which selects the route on a link by link basis in spite of choosing a route from predefined candidate routes. In [Mewanou2006], K most congested links of each of the candidate paths are determined and then a path chosen with the maximum number of continuous free wavelengths from the K most congested links from each of the paths. This approach reduces the number of blocked requests by selecting a wavelength continuous path.

Routing algorithms for wavelength routed WDM networks provides one or more best paths based on desired link/path metric to send data from source to destination node on one or more paths and other is used as protection paths. Some algorithms first calculate a set of candidate paths e.g. alternate path algorithms and use one best path to transfer the data. Some mission critical applications need a backup path for protection or restoration. A heuristic algorithm proposed by [Zhang2002] for solving the dynamic RWA problem considers the shortest path routing algorithm in a distributed manner. The algorithm creates an auxiliary graph for solving routing as well as wavelength assignment sub-problem. This algorithm considers the cost of wavelength and wavelength convertor to find the link weight. A static RWA algorithm proposed by [Manohar2002] to find the Edge Disjoint Paths (EDPs). A greedy EDP algorithm is developed to solve RWA problem with lesser complexity as compared to the standard ILP based solutions. The wavelengths are assigned to the selected paths using graph colouring algorithm. Use of EDPs reduces the number of unique wavelength requirement to setup the given number of light-paths as compared to standard solutions but still the bandwidth utilization is not efficient. In [Gurzi2009], RWA problem has been solved using maximum flow computation approach with wavelength converters in optical networks. They solved a single shortest path computation problem under wavelength continuity constraint. Gurjzi et. al. have attempted to solve the RWA problem in which a single working primary path is computed from the obtained set of paths under dynamic traffic. In his work they assumed that network nodes are equipped with the wavelength conversion capabilities due to which different wavlength on each hop can be used to establish a lightpath without strictly following the wavelength continuity constraint. Thus, wavelength converters have been used to relax the wavelength continuty constraint in WDM networks. The presence of partial or more number of wavelength converter in the network relax the problem constraints. However, authors have not considered the case of survivable routing problem in which pair of link disjoint paths are required under the wavelength continuity constraint and backup resource sharing assumption for survivability in the network. The static RWA algorithm developed by [Choo2006] employes the greedy approach in graph theory for obtaining available edge disjoint paths. It is based on the maximum flow which finds only the maximum quantity of edge disjoint paths where all capacities are set equal to one. Authors Choo et.al. do not considers the wavelengths or wavelength continuity constraint in the algorithm and wavelengths are searched to the chosen path separately. The algorithm uses the maximum number of stored paths for all possible connections for establishing a lightpath for each of the connection requests to reduce the time complexity. However, for a network with dynamic topology, the stored static edge disjoint paths need to be regularly updated to incorporate the topology changes. In all of these routing and wavelength assignment heuristic approaches route and wavelength assignment problem has been solved separately via decoupling the two subproblems.

In the proposed approach a survivable routing strategy for WDM networks to determine wavelength and the route simultaneously for an incoming lighpath connection request has been attempted. It solves the route and wavelength channel assignment problem at the same time, jointly without dissociating the two sub problems using maximum flow concept of graph theory.

4.2 System Model of Maximum Flow Networks

The maximum flow problem, finding a flow of maximum value on a network from a source s to a sink t, is one of the most fundamental problems with a wide variety of scientific and engineering applications and has been studied extensively. A flow network can be used to model the liquids flowing through pipes, parts through assembly lines, current through electrical networks, information through communication networks and so forth. Here we introduce some basics of flow network theory.

In network graph theory a flow network G(V,E) is a directed graph in which each edge $(u,v) \in E$ has a nonnegative capacity C(u,v) >=0 with two special vertices: the source vertex s, and the sink (destination) vertex t and each edge can receives a flow. If $(u,v) \notin E$, assume that C(u,v) =0. Every vertex lies on some path from source to sink.

A flow in G is a real valued function *f*: VxV → R that satisfies the restriction that the amount of flow on an edge cannot exceed the capacity of the edge and the amount of flow into a node equals to the amount of flow out of it except when it is a source node or sink node which has only the incoming flow. The three properties that a flow must full-fill are:

Capacity constraint: For all u, v , it requires $f(u,v) \leq C(u,v)$

Skew symmetry : For all u, v , it requires $f(u,v) = -f(v,u)$

Flow conservation : For all $u \in V - \{s,t\}$, it requires $\sum_{v \in V} f(u,v) = 0$

Using the above notations, maximum flow can be described as an objective function that maximizes the flow through the network, i.*e.*

$$\text{Maximize } \sum_{v \in V} f(s,v) \tag{4.1}$$

subjected to

$f(u,v) \leq C(u,v)$, for each $u, v \in V$

$f(u,v) = -f(v,u)$, for each $u, v \in V$

$\sum_{v \in V} f(u,v) = 0$, for each $u \in V - \{s,t\}$

$C(u,v) = 0$, if $(u,v) \notin E\ ((u,v))$

The above described maximum flow networks can be utilized to find all possible edge disjoint flow paths in a graph from a source node s to a destination node d. All the paths with available capacity are traced, these paths are known as augmenting paths. These are the paths through which we can send more flow and we repeat this process until we find no more augmenting paths. Thus, the results which will be found finally is the residual network with maximum flow.

Approaches used to solve the maximum flow problem in a given flow network is classified in two broad categories; one is augmenting path based approach and other one is preflow push-relabel based approach [Cormen2009]. Algorithms for solving maximum flow problem may be solved based on the idea of augmenting paths in which we first find a flow from s to t and then try to increase that flow until an optimal solution achieved, e.g. Ford Fulkerson [Cormen2009]. Other method endeavors for optimality and then adjusts to make the flow feasible in which first find the maximum flow from s to all its neigbours, at the risk of violation of some constraints and latter constraints can be fixed such that it leaves an optimal solution, e.g Push-Relabel algorithms [Goldberg1998] [Cormen2009]. Basic Ford-Fulkerson method performed is as follows:

```
start with initial flow as 0.
while there is a augmenting path from source to sink.
  add this path-flow to flow.
return flow
```

The problem was solved by Ford-Fulkerson based on the augmenting path method [Ford 1956]. The algorithm of Ford-Fulkerson assumes that input networks have integral or rational capacities and sometimes fail to correctly find a maximum flow or to halt for a network with irrational capacities. Further, [Edmonds1972] has been improved the Ford-Fulkerson algorithm by augmenting the flows along shortest augmenting paths through breadth first search. Push relabel algorithms work in more localized manner than augmented methods. Instead of examine entire residual network to find an augmenting paths, push relabel algorithm works on one vertex at a time looking only at the vertex's neighbors in the residual network and it does not maintain flow conservation property throughout their execution. In practice push relabel based method currently dominate augmenting path or linear programming based algorithms for the maximum flow problem. Another algorithm as suggested by Boykov et.al. in [Boykov2004], which belongs to the category of algorithms based on augmenting paths approach. Boykov et.al.'s method iteratively repeats the following three stages whose details can be found in [Boykov2004]:

Growth Phase: *search trees S and T grow until they touch giving a path from s to d*
Augmentation Phase: *the found path is augmented, search tree(s) break into forest(s)*
Adoption Phase: *trees S and T are restored.*

The detail of working of Boyko Kolmogorov technique of solving maximum flow of the flow network is as follows:

Assume that we have a directed graph G = (V, E) , a flow f, residual graph G_f , A_{list} and O_{list} which keep the lists of all active nodes, and all orphans respectively. S and T are two non-overlapping search trees with roots at the source s and the sink t, correspondingly. TreeCap(p→q) to describe residual capacity of either edge (p,q). The working procedure of technique as follows:

```
Initialization of $S \leftarrow \{s\}$, $T \leftarrow \{t\}$, $A_{list} \leftarrow \{s, t\}$, $O_{list} \leftarrow \{\emptyset\}$
while(true)
{   grow S or T to find an augmenting path P from s to t  // growth stage
    if ($P == \emptyset$) terminate
      augment on $P_{s\to t}$   //augmentation stage
      adopt orphans       // adoption stage
  }
```

Growth stage: In this stage active nodes acquire new children from a set of free nodes.

Growth Stage Procedure

```
Begin
  while $A_{list} \neq \{\emptyset\}$
  select an active node $p \in A_{list}$
   for (each neighbor q such that TreeCap(p→q) > 0)
     if ($TREE(q) = \emptyset$ )    // add q to search tree as an active node
          $TREE(q) := TREE(p)$,
          $PARENT(q) := p$,
          $A_{list} := A \cup \{q\}$
       if ($TREE(q) \neq \emptyset$ && $TREE(q) \neq TREE(p)$)
         return ( $P = PATHs\to t$ )
     end for
   remove p from $A_{list}$
 end while
return $P = \emptyset$
End
```

Augmentation stage: In this stage the found path is augmented.

Augument Stage Procedure

```
Begin
 Determine bottleneck capacity $\Delta$ on $P_{s\to t}$
   Update the residual graph by pushing flow $\Delta$ through $P_{s\to t}$
   for ( each saturated edge (p, q) in $P_{s\to t}$)
       if ($TREE(p) = TREE(q) = S$ )
           $PARENT(q) := \emptyset$
```

```
          $O_{list} := O \cup \{q\}$
      if $(TREE(p) = TREE(q) = T)$
          $PARENT(p) := \emptyset$
          $O_{list} := O_{list} \cup \{p\}$
  end for
End
```

Adoption stage: In this stage all orphan nodes in *O* are processed until *O* becomes empty.

Adoption Stage Procedure

```
Begin
  while ($O_{list} \neq \emptyset$)
    Select an orphan node $p \in O_{list}$
      $O_{list} := \{ O_{list} \} - \{ p \}$
    find q  a valid parent of p among its neighbors
      if( q valid parent of p)
          $TREE(q) = TREE(p)$
          $TreeCap(q \rightarrow p) > 0$
          Set origin of q =source s  or sink t
  end while
End
```

In this method two search trees are maintained, one from the source and the other from the sink. These trees are reused to speed up the search hence never start building them from scratch. Other augmenting path algorithms determines shortest paths from source to sink and augment them by bottleneck capacity and then adding it to the total flow. Boykov method does not find a new shortest path from source to sink for each step, instead of that it builds up two search trees and reuses them at each augmenting phase. These search trees can be reused from one max flow computation to the next computation. From all of these available method to solve max flow network problem of routing, we prefer to use the method suggested by Boykov et.al. due to its more feasibility to the routing problem of network.

4.3 Overview of Resource Aware Multi-lightPath Routing (RAMPR)

The proposed routing algorithm considers the maximum network flow technique for the survivable protection routing in WDM optical network meeting the wavelength continuity constraint. The survivable routing problem addressed in this work is based on network topology, traffic load and wavelength resource of the network to determine multiple lightpaths. This is achieved by the maximum flow between any given source and destination node pair in the network which is based on the graph theory of maximum flow technique. The optimal disjoint multiple path maximizes the network performance. The multipath route computation in WDM networks helps to improve the network efficiency. The proposed approach determines the wavelength continuity constraint multipath to solve the survivable routing and wavelength assignment problem jointy without separating the route selection from the wavelength assignment. It finds the route and wavelength at the same time without solving the two subproblems separately and individualy. Hence, the proposed routing using wavelength continuity constraint routes selection and channel assignment simultaneously, making it more efficient and reliable in a large scale network environment.

4.3.1 RAMPR using Maximum Flow Network

This maximum flow technique based algorithm has been proposed which is used for a wavelength continuity constraint based routing in WDM optical networks. It is used to establish a wavelength continuous disjoint pair of multipath between a given source node and destination node pair.

4.3.1.1 Physical Topology Transformation

Physical network topology can not be directly applicable to maximum flow technique. The physical network topology which is used as a flow network requires to be converted into a graph, which can allows us to solve the survivable routing and wavelength assignment problem under the wavelength continuity constraint. A given network of N nodes and L links having total W wavelengths on each of the links can be represented as a W layered graph between any two node's pair as shown in the Figure 4.2. This is similar to a wavelength graph where each edge in the graph represents a wavelength. The number of edges in such graphs can be found by the product of number of wavelengths W and number of links L. Each edge of the flow network graph has been assigned weight value 1 if the corresponding wavelength is free or it has been assigned weight value 0 if corresponding wavelength is busy. Edge may be assigned a weight value 2 (if corresponding wavelength is used by single backup path) or more (depending on how many backup paths are using that corresponding wavelength) to an edge if the corresponding wavelength is shareable among more than one backup lightpaths.

Hence, at any point of time a connected edge which have capacity value of 1 indicates the presence of that wavelength while capacity value 0 of the edge shows that this wavelength is busy and will not be available for primary paths. When at any point of time a connected edge have been assigned capacity value of other than 1 and 0, it indicates that corresponding wavelength is shareable and it can be assigned to the other forthcoming backup protection paths. Such edges has been assigned the capacity 2 or greater than 2, which indicates the total count of wavelength which has been shared among backup paths. For example, edge capacity of value 2 indicates that the wavelength is used by a single backup path. Weight values are increased on the basis of sharing of wavelengths among two or more backup paths under the assumption of backup multiplexing based resource sharing. Whenever a backup path uses a wavelength which has been already assigned to a backup lightpath, corresponding wavelength's shareability count increases by one. Thus the capacity value of corresponding edge is also incremented. This sharability count represents the number of backup paths which are sharing that wavelength and it is assigned as the capacity weight value to that edge. Hence for each new lightpath which is established on a certain wavelength, the edge corresponding to 0 indicate the unavailability of this wavelength at that moment. Similarly, once a lightpath terminates; the edges corresponding to that wavelength is restored to the value of 1 in the wavelength graph which indicates its availability for incoming lightpath request. Primary paths can use only free wavelengths while backup path may use either free or shareable wavelengths. However, shareable wavelengths are preferable in the establishment of backup paths to optimize the network resource.

Figure 4.1 shows a physical topology consists of 5 node and 7 fiber links. Each fiber link is assumed to carry three wavelengths.

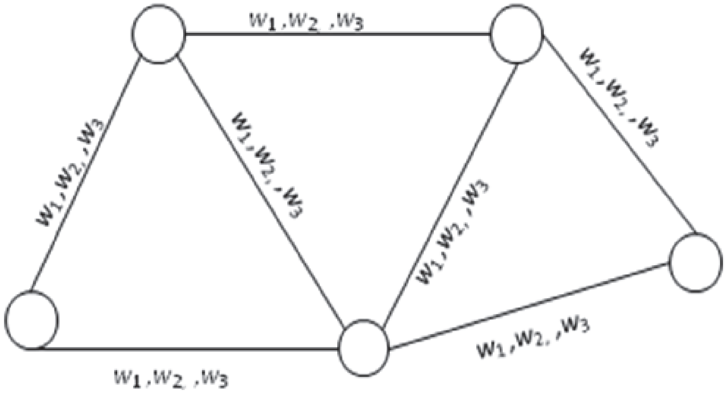


Figure 4.1: Physical Topology

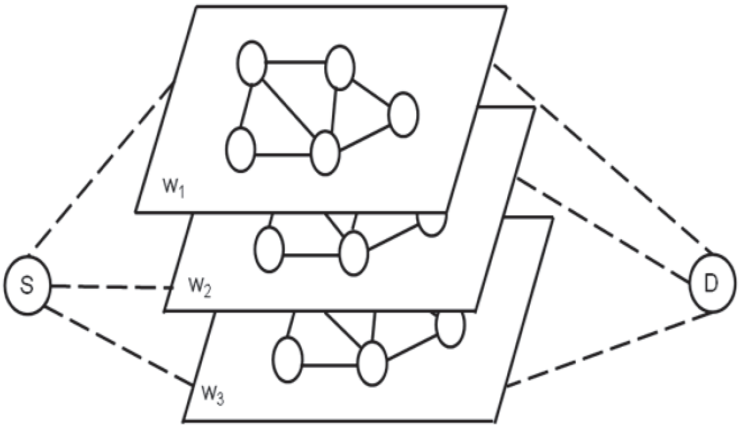


Figure 4.2: Logical Topology

Generally, in order to solve the survivable routing and wavelength assignment (SRWA) problem, first we have to find link disjoint routes and then select a wavelength for primary path and backup path that employs the wavelength continuity constraint. Survivable routing and wavelength assignment problem becomes more complex due to the wavelength continuity constraint. Wavelength assigned to the backup path by using backup multiplexing technique to improve the network resource utilization. However, transformation of physical topology enables us to determine both the route and wavelength of a connection request at the same time simultaneously through maximum flow network of graph theory. Thus, the route selection and wavelength assignment problem takes place jointly at the same time without the requirement of decoupling the problem. This type of network representation makes the route selection and wavelength assignment process simpler and coupled. By transforming the network topology in the form which is suitable to the maximum flow technique such that wavelength continuity constraint is also representable into the network topolgy.

Figure 4.3 represents the transformed topology which has obtained for the physical topology shown in Figure 4.1. Each node is replicated equal to the total number of wavelengths in each fiber link and for each node pair, added the edges equal to the number of wavelengths between each node pair in the physical topology. The capacity weight value of 1 on each edge reflects the availability status of a wavelength. For example in Figure 4.4 all wavelengths are free in the topology. Similarly Figure 4.5 shows few wavelengths are free and few are busy. In Figure 4.6 edge capacity represents busy wavelength and wavelengths which has been used by backup lightpaths i.e. a shareable wavelengths on the links.

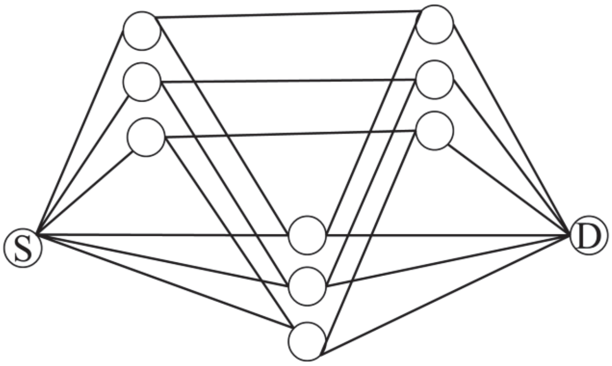


Figure 4.3: Transformed Physical Topology as Flow Network

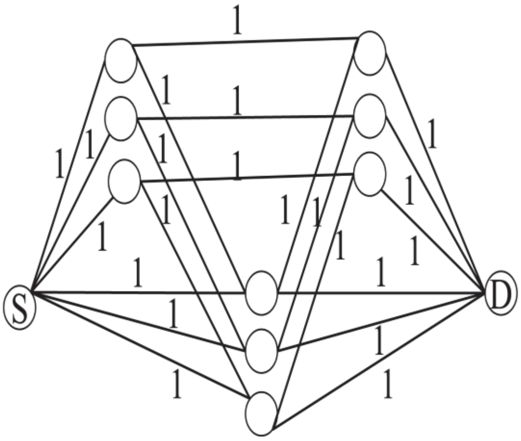


Figure 4.4: Transformed Flow Network Topology with Free Wavelengths

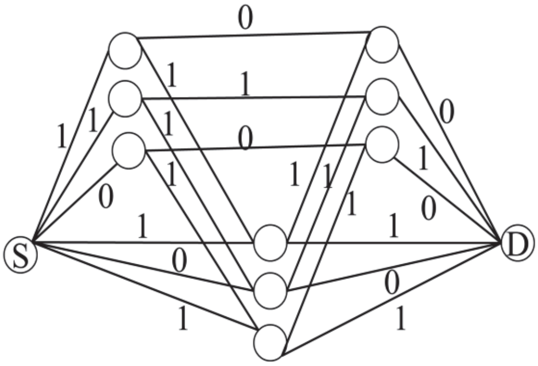


Figure 4.5: Transformed Flow Network Topology having Busy and Free Wavelengths

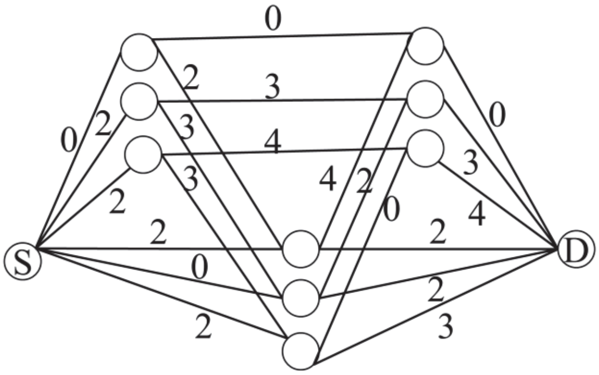


Figure 4.6: Transformed Flow Network Topology with Shareable Wavelengths

It is not necessary that the physical topology can be transformed for each new connection request. Physical topology is static and fixed. Transformed physical topology is kept static and the cost value of edge is required to be computed and updated for each incoming connection request. When a new lightpath is established, the edge value corresponding to that wavelength changes from 1 to 0 and after the termination of a lightpath corresponding wavelength changes back from 0 to 1. If a lightpath is used by a backup path, the weight value of corresponding wavelength is incremented which represents that correspondent wavelength is shareable between backup paths and after the termination of a backup path capacity of corresponding edges are decremented. Each edge in transformed topology can carry only either one unit of flow or more than one one unit of flow due to non-negative integer valued function of the flow.

4.3.1.2 RAMPR using Maximum Network Flows Algorithm

In the literature various heuristic solution to solve the routing and wavelength assignment problem have been proposed [Zang2000]. The several routing methods such as fixed routing, fixed alternate routing, adaptive routing and several wavelength assignment methods such as first fit, most used, best fit, least used etc. have been proposed, which are evaluated analytically and experimentally. All the routing and wavelength assignment algorithm available in literature mostly performs in two steps: first route selection is performed which optimizes one or two network performance metrics and thereafter, wavelength assignment is performed over the computed routes that respect the wavelength continuity constraint or vice versa. In this two sequential step process, we may not always able to find route and a continuous wavelength for an incoming connection request in network and may also suffers from trap problem. In case either the route or a channel may not found, then the request is dropped or again apply the same procedure for another attempt to succeed. In the proposed approach of maximum flow network based multi-lightpath survivable routing has specified as a graph network G (N, E) of N nodes and a set E edges and a source node s and destination node d , $s,d \in N$, and an integer $k > 0$. The goal is to find all possible primary and backup lightpaths from s to d, such that the lightpaths do not share common links i.e. wavelength link disjoint paths. In maximum flow network problem several source to destination (sink) pairs try to maximize their own flow at the same time. RWA problem is NP complete problem for dynamic traffic; hence, to determine an optimal solution is not likely to be possible. Hence, search for the local optimum paths using maximum flow may be beneficial for each source destination request pair. Therefore, for WDM optical networks each physical edge has a capacity which is equal to wavelength channel and maximum flow paths represent the maximum number of lighpaths that can be established for a given source-destination pair of requests. Selection from flow path can optimize the network resources and allows to maximize the amount of lighpaths that can be established between a source and destination. Pseudo code of the proposed algorithm is shown in Algorithm 4.1. This method first converts the physical topology in a format that allows us to solve the routing and wavelength assignment problem simultaneously at the same time. Edge weights are assigned to transformed topology as described above. The transformed topology enables feasibility of the route and channel assignment process to take place together simultaneusly. Once the topology is transformed into a max flow network, all the maximum flow paths are computed using the suitable maximum flow network algorithm. It determine both the primary and backup lightpath for each arriving connection request. These computed paths are link and wavelength disjoint paths which obey the wavelength continuity constraint.

Algorithm 4.1: RAMPR-SRWA Algorithm

Input: Physical network topology $G(N, L, W)$; Set of arriving demands R whose source node is s and destination node is d. Required bandwidth is a wavelength.

Output: Disjoint pairs of working Lightpath and Backup Lightpath.

```
RAMPR_SRWA( G(N,L,W) )
{ begin
    For ( $\forall n \in N$ of physical topology G) do
        Replicate node n of G up to $n_1, n_2, n_3 ......n_w$ in G' logical topology
    endfor
    For ( $\forall$ link (n, m) $\in$ L of physical topology) do
        Create edges $(n_1, m_1), (n_2, m_2), (n_3, m_3),........, (n_w, m_w)$ into G' logical topology
    endfor
    For ( each incoming connection request $R_{s\,d}$ ) do
        For ( $\forall$ edge $(n_\lambda, m_\lambda) \in$ L of Logical topology G' where $\lambda \in W$) do
            if ($\lambda$ is free)
                Assign capacity value of edge link $(n_\lambda, m_\lambda)$ to 1
```

```
        else if ($\lambda$ is busy)
                Assign capacity value of edge link ($n_\lambda$, $m_\lambda$) to 0
        endif
    endfor
  Compute all paths using BoykoKolmogorov technique of max flow algorithm over
    transformed topology

  if (Paths not found) then
      Block the connection request and reject
  else
      Arrange all the wavelength continuous paths according to path length
      Select the optimal shortest path as primary lightpath
  endif
  For ( $\forall$ edge ($n_\lambda$, $m_\lambda$) $\in$ L of Logical topology G' where $\lambda \in$ W) do
      if (edge (n, m) belongs to primary lightpath )
              Assign capacity value of edge link ($n_\lambda$, $m_\lambda$) to 0
      if ($\lambda$ is shareable)
          Assign capacity value of edge link ($n_\lambda$, $m_\lambda$) equal to number of backup
                lightpaths sharing that $\lambda$
      else if ($\lambda$ is free)
                Assign capacity value of edge link ($n_\lambda$, $m_\lambda$) to 1
      else
              Assign capacity value of edge link ($n_\lambda$, $m_\lambda$) to 0
      endif
  endfor
  Use the transformed Physical topology for Backup path computation
  Compute all paths using BoykoKolmogorov technique of max flow algorithm over
    transformed topology

  if (Paths not found) then
      Reject the connection request and Drop from the network
      Release all the wavelengths assigned to primary path
  else
      Arrange all the wavelength continuous paths according to its maximum path
        flow value
      Select the best path which have a largest maximum flow value as Backup
        lightpath
      All remaining paths kept as restoration protection paths at source node without
        reserving channel which can be used during restoration process
  endif
endfor
```

4.4 Performance Analysis

Extensive simulation has been performed to evaluate the performance of the proposed approach and compared with other three routing strategies. We have simulated the dynamic network environment over three representative test network topologies shown in Figure 4.7, Figure 4.8 and Figure 4.9. The US IP network topology in Figure 4.1 consists of 24 nodes and 43 links, EON network topology of Figure 4.8 consists of 19 nodes and 39 links and NSFNET topology of Figure 4.9 has 14 Nodes and 22 Links. The three different network topologies have been considered with different number of links, nodes and average nodal degree to validate the startegy and to show that analysis are not specific to a given topology for general network acceptability. In the simulation model each of the nodes in the network is capable to generate lightpath request to a random destination node. Each link in the network assumed to have same W=10 wavelength channels. Assume that connection requests arrives for a random source and destination pair. The bandwidth required for each connection request is satisfied by one wavelength and there is no waiting queues in network. Hence if a connection request is not satisfied due to limited network resource or route cannot be determined, then it is abandoned immediately from the network and blocked. In the simulation run upto 400 requests are generated and results are averaged over 40 such simulation runs for the evaluation of network performance. First Fit wavelength assignment algorithm is used for primary path and shared backup multiplexing technique has used for channel assignment to backup paths.

The proposed algorithm is compared with the i) shortest path routing, ii) k-shortest routing and iii) fixed alternate routing method, wherein a set of candidate routes for every source destination node pair is precomputed. In k-shortest path strategy in the simulation k=5 possible path has been considered. Value of k=5 has been taken to consider the possibility of establishment of lightpath, when we have at that moment k paths before the request is dropped and rejected from the network as compared to the consideration of single path. The candidate routes of a source destination pair are chosen to be link-disjoint which ensures failure-independent lightpath restoration. Proposed approach finds all the link-disjoint routes in parallel without any contention among them. All of these methods used for comparison route lightpaths with fault tolerance capability by providing backup protection path(s) at the time of honoring the incoming connection requests. The two metrics used to measure the performance are blocking probability and improvement gain in blocking probability which gives an idea of relative performance improvement of one approach against the other.

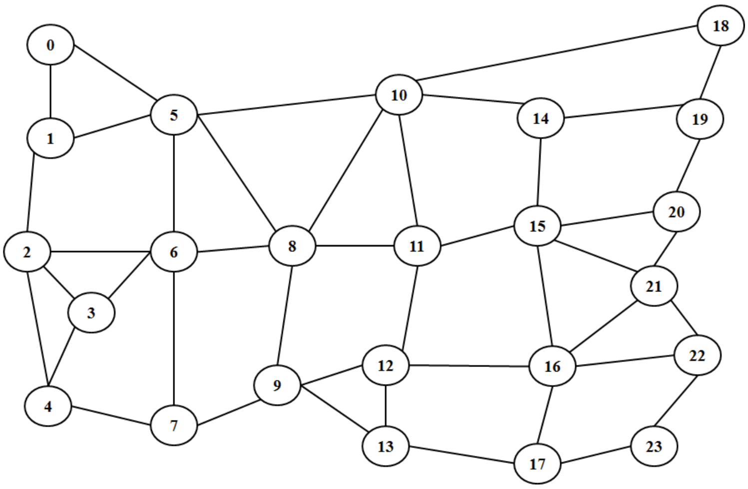


Figure 4.7: US IP Network Topology [Venkatesh2007]

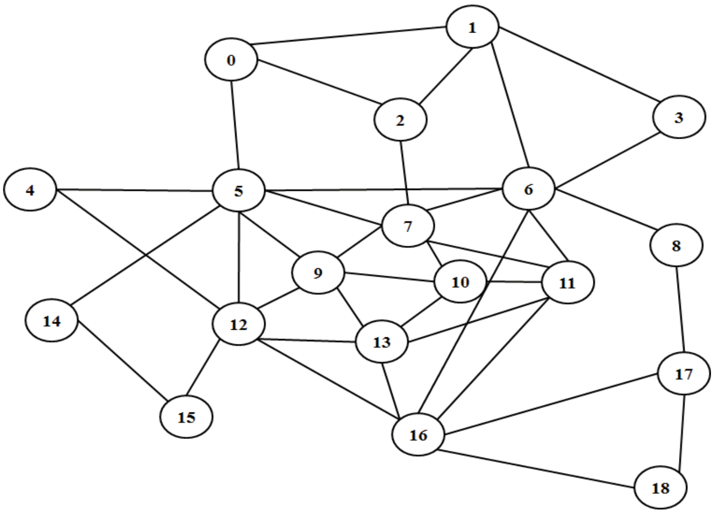


Figure 4.8: EON Network Topology [Chu2003]

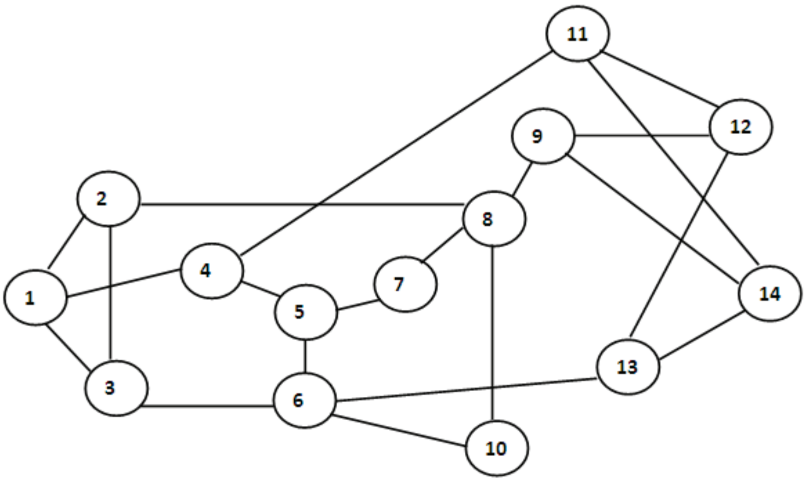


Figure 4.9: NSFNET Network Topology [Venkatesh2007]

4.4.1 Analysis of Blocking Probability Performance

The performance of the proposed algorithm is plotted and compared in Figure 4.10, Figure 4.11 and Figure 4.12, the call connection blocking probability is plotted as a function of incoming connection request traffic on the USIP, EON and NSFNET network topologies which are shown in Figure 4.7, Figure 4.8 and Figure 4.9 respectively.

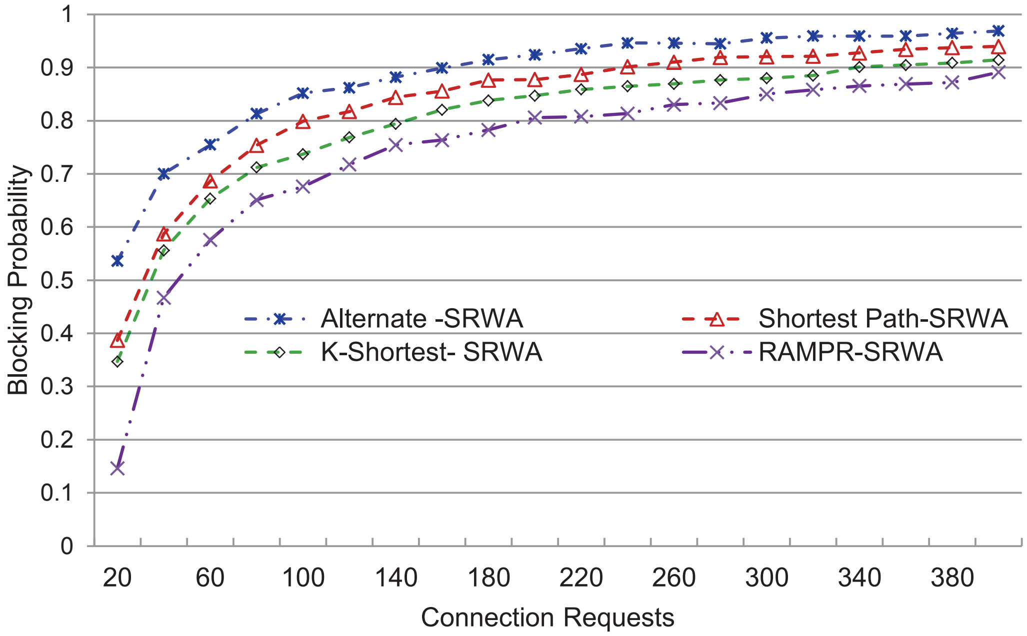


Figure 4.10: Blocking Probability on USIP Topology

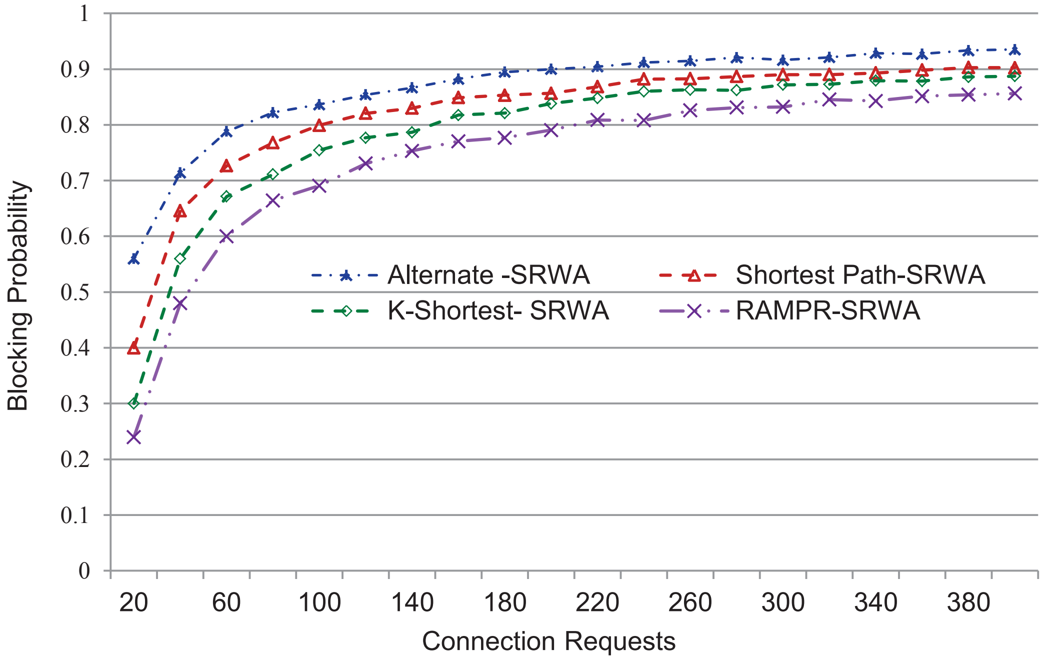


Figure 4.11: Blocking Probability on EON Topology

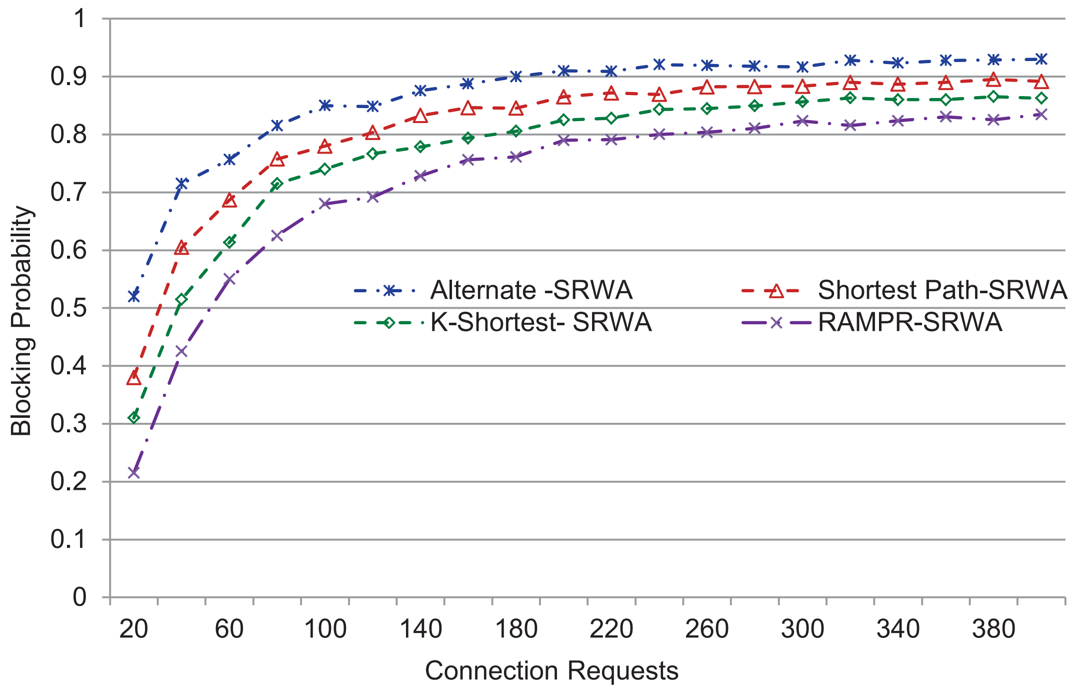


Figure 4.12: Blocking Probability on NSFNET Topology

The results of the graph demonstrate the usefulness of maximum network flow based RAMPR survivable routing. The performance achieved by proposed method is significantly higher as compared to the fixed alternate routing, shortest path and k-shortest path routing. Result show that the blocking probability increase with the increase in traffic load of the network. The blocking probability of proposed method is significantly lower even at higher traffic load of incoming connection requests than to the alternate routing, shortest routing and k-shortest path routing.

At higher traffic load, less spare resources are available in the network so blocking probability increases as with the increase in traffic load. In particular, plot shows that proposed method for survivable routing can significantly perform better and resource efficient than other three conventional approaches. Because in conventional approach wavelength selection does not happen at the time of route selection.

4.4.2 Analysis of Blocking Probability Improvement Performance

Quality and adaptability of an approach is also characterized on the basis of relative performance improvement in the network on the basis of adopted algorithm. In the present analysis the percentage improvement of the blocking probability of maximum flow network based survivable routing for the incoming connection requests based on USIP topology, EON topology and NSFNET network topology has been considered.

The relative performance of RAMPR routing with respect to various conventional routing strategy has been investigated and the simulation results have been presented in Figure 4.7, Figure 4.8 and Figure 4.9 respectively.It haserved from the figures that the proposed approach shows an improvement in blocking probability as compared to fixed alternate routing, shortest path and k-shortest path routing algorithm. In all plots, percentage improvement in blocking performance of proposed algorithm relative to alternate routing algorithm is higher than the performance improvement relative to shortest and k-shortest path routing algorithm and is much distinct at lower lightpath connection request. It is inferred that maximum flow based routing algorithm performs significantly better relative to all the other three approaches. Plots show that percentage improvement in blocking probability decreases with the increase in rate of incoming lightpath connection requests. At lower requests arrival rate in the network, blocking probability is low and relative benefit in terms of blocking improvement is high in comparison to higher requests arrival rate.

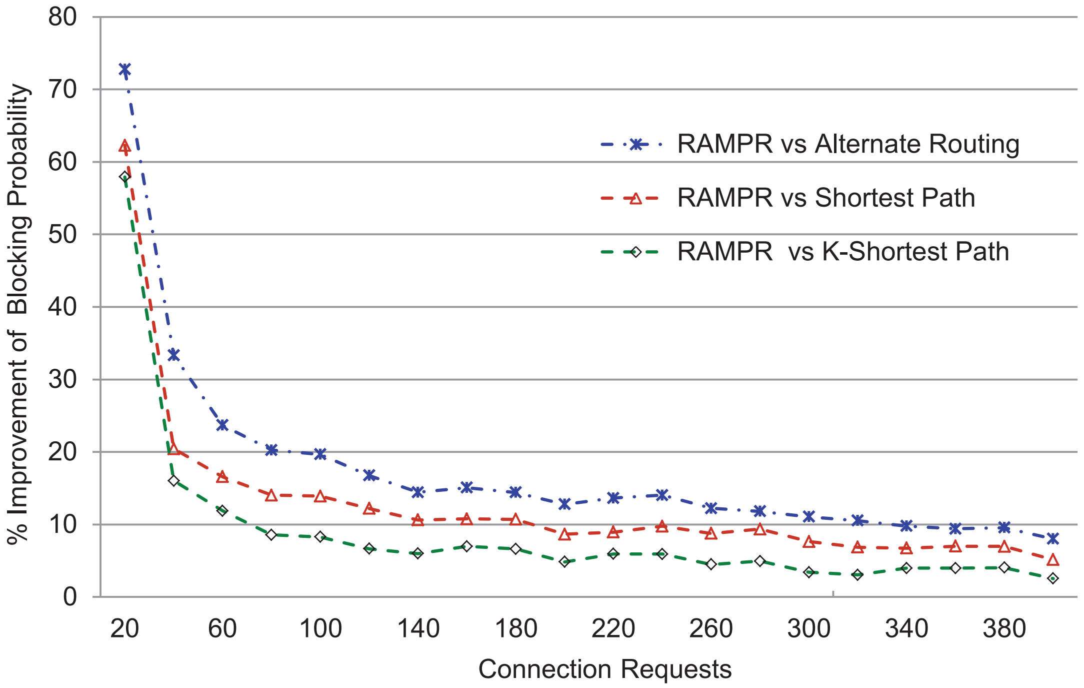


Figure 4.13: Improvement of Blocking Probability Performance on USIP Topology

It is observed that call blocking probability increases at higher arrival rate of connection requests but relative percentage improvement of blocking probability is not increasing as fast as equivalent to blocking probability itself. That's why it is evident from graphs that percentage improvement are decreasing in all the three network topologies. Overall observation is that the performance of maximum network flow based survivable lightpath protection routing is significant and promising.

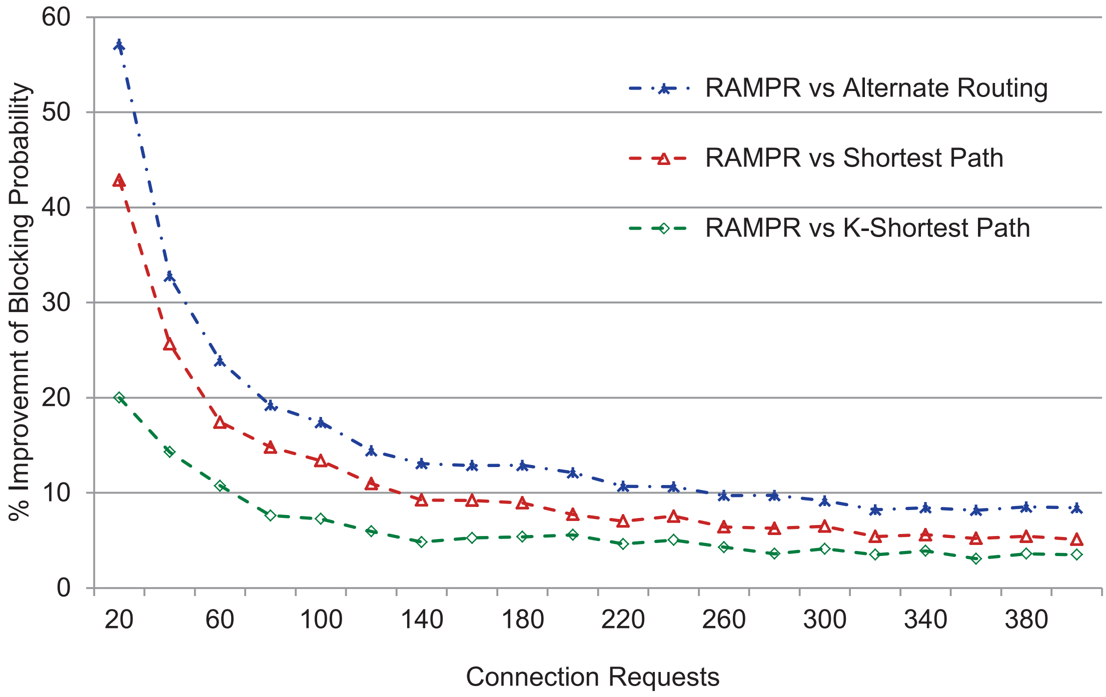


Figure 4.14: Improvement of Blocking Probability Performance on EON Topology

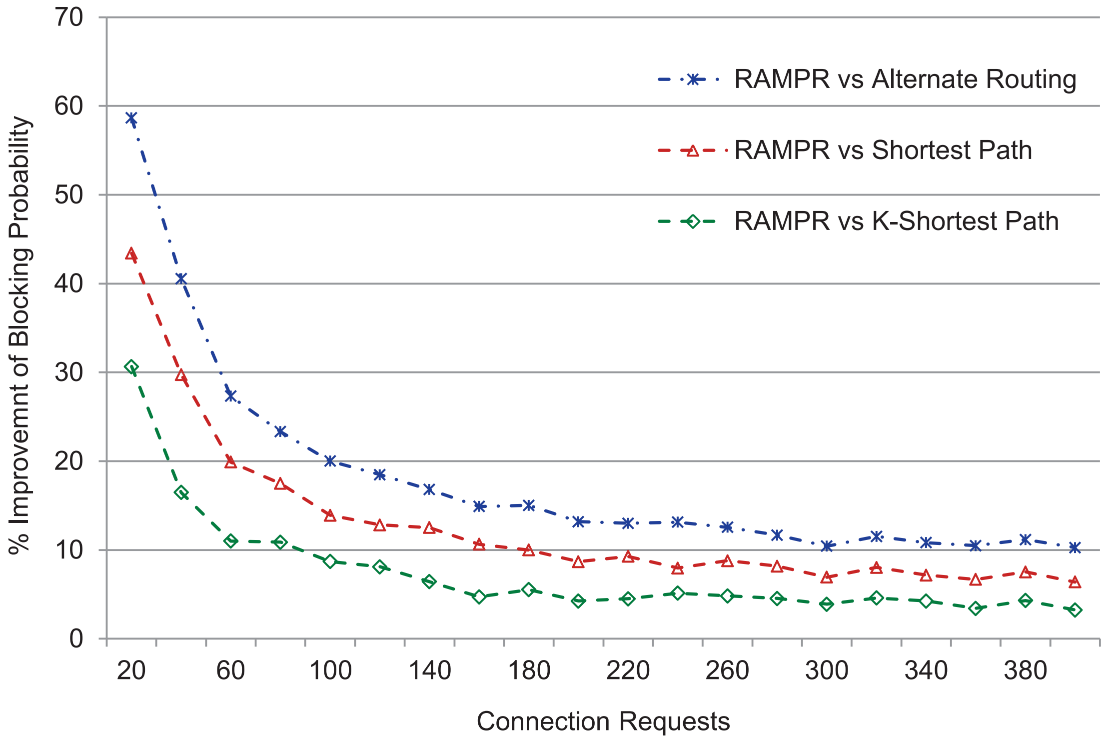


Figure 4.15: Improvement of Blocking Probability Performance on NSFNET Topology

It is also observed from these simulation studies that the blocking performance behavior of all the considered routing algorithms claims a similar qualitative nature in all the three network topologies considered. It has further been observed that the proposed algorithm out performs at lower connection requests and this improvement is more significant in USIP topology, which may be attributed to the presence of more number of nodes, links and larger average nodal degree as compared to other two.

4.5 Summary

In this chapter multipath survivable routing mechanism has been analysed and simulated in the Wavelength Division Multiplexing (WDM) system, which imposes a wavelength continuity constraint in routing. The simulation results show that the multi-lightpath mechanism can improve the wavelength resource utilization significantly. Further in this chapter a heuristic survivable routing solution has been proposed, evaluated and compared with the other conventional WDM network routing approaches. The proposed resource aware routing employs wavelength assignment strategy using the maximum flow network of graph theory. The survivable lightpath routing based on maximum network flow concepts, has been used to determine the routes and available wavelength channels simultaneously. In this process multiple lighpaths are available for each request, to select one or more paths to enhance the network efficiency. Simulation study under the three different network topologies confirm that the proposed maximum flow network based routing for the survivable network has a comparatively lower call blocking performance as compared to the other cases of fixed alternate routing, shortest path and k-shortest path routing approach.

CHAPTER - 5

Nature Inspired Survivable Routing Algorithm

In telecommunication networks, the optical WDM technology has extensively been deployed to meet the ever increasing demands of bandwidth for the high speed data transmissions. Optical fiber has high data transmission capability and is also capable to accommodate multi-channels in WDM networks to meet the resilience routing requirements for uninterrupted data communication in case of link failures. Thus, in case of link failure the network survivability and maintaining quality of service (QoS) require extra resource provisioning and routing management facilities [Ramaswami2002] [Mukherjee2006].

In this chapter, our objective is to develop a survivable protection routing algorithm to meet the requirements of dynamic network adaptability, robustness and distributiveness by applying an Intelligent Water Drop (IWD) based algorithm. The IWD based heuristic is specially introduced here to tackle the constrained multicommodity optimization problem in survivable routing. In the present chapters IWD based heuristic framework has been proposed to find the optimal link disjoint paths between a source-destination node pair to provide single link failure protection in case of WDM network. The simulation study shows that the proposed IWD based survivable RWA algorithm can achieve significantly better performance than the fixed alternate routing, shortest path routing, ant colony based routing and bee colony based routing for survivable routing algorithm in terms of blocking probability and resource utilization. The simulation results demonstrate the ability and efficiency of proposed IWD model for solving the survival routing problem in WDM optical networks.

5.1 Related Work

In all-optical networks, data are routed through optical channels called lightpaths. In such a system, determination of a route and wavelength for a connection request is known as Routing and Wavelength Assignment problem. Routes can be computed either for a connection request, which is known in advance (static case) or these connection requests are arriving randomly (dynamic case). In the problem of survival routing in WDM network for lightpath protection under dynamic traffic, the fundamental concern is to find a pair of link disjoint paths from a source to destination node for each incoming request to establish the lightpaths successfully, which can withstand against a single link fault. In dynamic routing of a restorable survivable network, connection require a pair of link-disjoint primary and backup lightpath to be found online when a connection request arrives in the network.

The problem of finding such a link disjoint optimal path pair in a wavelength continuous network turns out to be NP-complete [Zhang2003]. Thus, a heuristic for finding a near optimal solution with reasonable computation time is usually preferred [Lin2008]. Routing schemes are categorized into fixed routing and fixed-alternate routing or adaptive routing. Adaptive routing scheme yields the best performance because the route is determined based on current network state. The route computation through adaptive RWA solution requires mostly special support from control protocol to obtain the up to date global state of the network. Hence it has higher computational complexity. Heuristic approaches consider the tradeoff between performance and complexity in searching for the route and wavelength after the lightpath request arrives. Heuristic algorithms can also suffer from high setup delay and control overhead. Heuristic algorithms required up to date network state, which makes them practically not much feasible and applicable for a large complex and highly dynamic WDM networks. Most of the heuristic algorithms need global network status information and it must be refreshed frequently, so that each node can maintain global network status information. Otherwise, the latest change of the network status cannot be reflected correctly. So the quantity of communication overhead cost and the source node's computation increase in large-scale networks while dealing with more constraints.

Different solution methods have been proposed for solving survivable routing problems, some of them are definite and give an optimal solution. Some other algorithms provide responses that are close to the optimal one, neural networks and metaheuristic algorithms, for examples, Ant colony optimization algorithm, Artificial bee colony Optimization algorithms, Cuckoo optimization algorithm etc. by adding different constraints to the related algorithms, they seek to find optimal responses using different search methods and provide the responses close to the optimal one. The nature-inspired optimization methods outperform the conventional methods when solving the routing problem in a distributed manner for a survivable WDM optical network [Ducatelle2010]. There are several research works that use intelligent nature inspired algorithm for routing in various computer networks [Wedde2006]. Nature inspired network routing algorithm harvests the network dynamics which affects performance significantly. Actually, it implements the strategies which are used by nodes of the network to determine a route to send data from source to destination. The use of computers to model nature, and study of nature to improve the usage of computer has become a challenging and an interesting research area. Many algorithms came out from this research. The collective intelligent behavior of insect or animal groups in nature such as flocks of birds, colonies of ants, schools of fish and swarms of bees etc. have attracted the attention of researcher community [Farooq2008]. The aggregate behavior of insects or animals is called swarm behavior. Researchers have studied these collective behaviors of nature to model biological swarms, which is modeled as a framework for solving complex real problems. Swarm intelligence has various advantages such as scalability, adaptability, fault tolerance, autonomy and parallelism. Swarm Intelligence is a branch of artificial intelligence, which is based on the collective, collaborative and cooperative actions of individuals [Kassabalidis2001]. These swarms, through a complex interaction of individuals without supervision collaboratively solve the complex combinatorial optimization problem. Many species in nature are characterized by swarm behavior. These virtual swarms or artificial agents communicate among themselves, cooperate, collaborate, exchange information and knowledge and perform some specific tasks in their environment.

The Bees Algorithm is an optimization algorithm inspired by the natural foraging behavior of honey bees to find the optimal solution Artificial bee colony algorithm algorithm was first presented by Karaboga and later by [Akay2012] modified it as a new meta-heuristic approach. It has been inspired from the intelligent behaviour of bees movement, searching for food. It has been formed based on food-seeking of bees which are divided into three groups in the real world: Employed, onlooker, Scout bees. The characterized interacting collective behaviour of specialized individuals, distributed simultaneous tasks performed, and self-organization, leads to the colony as an organized teamwork system. The Artificial Bees Colony (ABC) is an iterative algorithm, where each artificial bee agent is assigned to a solution which is generated randomly; then in every iteration, each agent uses neighbourhood operator to find a new solution. The fitness (nectar amount) of the newly found solution is evaluated per iteration; if it is found higher then replace the previous solution by the newer one. Each cycle of the ABC algorithm comprises three steps: first, sending the employed bee to the possible food-source positions (solutions) and measuring their nectar amounts (fitness values); second, onlookers selecting a food source after sharing the information from the employed bees in the previous step; third, determining the scout bees and then sending them into entirely new food-source positions.

At the beginning of the search process all artificial agents are located in the hive. Bees depart from the hive and fly through the artificial network from the left to the right. Bee's trip is divided into stages. Bee chooses to visit one artificial node at every stage. Each stage represents the collection of all considered origin-destination pairs. Each request is comprised of an origin and destination linked by a number of routes. Lightpath is a route with assigned wavelength chosen by bee agent. Bee agent's entire flight is collection of established lightpaths.

The general working of the bee colony algorithm is described as follows:

```
1. Initialize: every bee set to an empty solution
2. For every bee do the forward pass
    i) Set k=1 //Counter for constructive moves in the forward pass
    ii) Evaluate all possible constructive moves
    iii) Choose according to evaluation one move
    iv) Increment k;
    v) if k less than number of constructive move during one forward move
        go to step (2.ii)
3. All bees send back to the hive //backward pass start
4. Allow bees to exchange information about quality of the partial exploration.
    Every bee decides whether to abandon the created partial solution and continue
    its exploration without recruiting the nestmates or become a recruiter or to
    become a follower
5. For every follower choose a new solution from recruiters
6. If best solution obtained is better than previous solution update the best
    known solution.
7. If stopping condition is not met go to step 2.
8. Output the best solutions.
```

Bee Colony optimization is inspired by bees behavior in nature. It is used for simulating the intelligent behavior of honey bees. The aim of bees is to discover the places of food sources involving high nectar amount and finally mark the one with the highest nectar amount as problem solution [Karaboga2014]. ABC optimization algorithm has been used successfully to various engineering problems. In [Wedde2004] authors have introduced a fault-tolerant adaptive routing algorithm inspired from dance language and foraging behavior of honey bees. The author uses bee agents for the purpose of finding suitable paths between sites, by extensively borrowing from the principles behind the bee communication for packet switch network. [Kavian2013] [Markovic2010] [Goran2007] applied the bee colony optimization algorithm to solve the RWA problem of WDM optical network for the static case of traffic. In his approach bee exploits the resource availability of network to determine the requested lightpaths in WDM optical network. In [Schoonderwoerd1997] an adaptive routing algorithm for telephone networks using the ants-based agents has been proposed. The purpose of agents of his algorithm is to maximize the accepted rate of incoming loads. Using the principle of dynamic programming, algorithm which is proposed by Schoonderwoerd is further improved by Bonabeau [Bonabeau1998].

Ant colony optimization (ACO) has been proposed by Dorigo inspired by the swarm based behavior of real ants to find the shortest paths. Ants deposit a chemical material called pheromone, when they are walking. Collectively ants can present a useful behavior for performing tasks such as discovering the shortest path between a food source and the nest. In order to perform ACO for routing, an idea should be used to mimic the behavior of real ants with artificial ones walking around the problem graph of network. The colony shares information through stigmergy, that is a form of indirect communication used by ants in nature by laying a chemical substance called pheromone. The pheromone induces changes in the environment, which can be sensed by other ants. An artificial ant can be implemented as a simple procedure that simulates the laying and sensing of pheromone. Each ant starts from the source node s and explores the network trying to find the destination node d. Ants are guided by the pheromone and find their destination. An ant needs to be able to find the end of the path until destination is reached. When the ant finds the destination node, it returns to the source node in the reverse direction by adding pheromone to the link. Furthermore, the colony consists of a data structure that generates ants and records the nodes that they pass.

The general working of the ant colony algorithm is summarized as:

1. Initialize the pheromone trails by setting the relevant parameters.
2. While the stopping condition is not met, do:
    - 2.1. For each ant in the colony do:
        - i) Construct a solution by repeatedly applying the transition rule;
        - ii) Improve the solution by the local search;
        - iii) If the solution is improved one, update the best solution constructed so far and the corresponding objective value as well.
    - 2.2. Applying global updating rule modify the pheromone trails.
3. Obtained the best solution.

Various swarm based intelligent algorithms have been proposed for the survivable RWA problem in WDM networks. In [Dorigo1991] Ant Colony Optimization algorithm simulates the behavior of ant colonies and Particle Swarm Optimization (PSO) algorithm, [Kennedy1995] mimicking flocks of birds are the most popular intelligence based optimization algorithms. Ant colony optimization is a probabilistic technique used for solving complex computational problems, such as finding optimal routes in networks. This technique uses pheromone trails laid by ants along different routes to find the optimal paths on the dynamic network. AntNet [Caro1998] is an adaptive agent-based routing algorithm in which the paths are determined and computed with the help of forward and backward ant agents. An ACO-based algorithm is used to solve RWA problem for optical networks. Additional works on ACO include [Ngo2006a], [Ngo2006] and [Gonzalez2003]. In the ACO-based RWA algorithm, ants leave pheromone trails behind which help other ants find optimal paths in the network. Ants are launched on a separate control plane and forwarded on the WDM network to set up the connection request.

ACO is applied in the static RWA problem to minimize the total number of wavelength requirement of the given networks and traffic matrix [Varela1999]. A greedy wavelength assignment method assigns the lowest available wavelength to each link. His approach is not applicable to dynamic RWA problem. In [Garlick2002] an algorithm is proposed which can be applied to dynamic RWA problem. In Garlick's approach paths are ranked based on the congestion level of the links. He uses a number of mobile agents to search for paths and there is no cooperation among agents which are launched from nodes to explore the network states. Proposed approach suffers from high connection setup delay.

Routing process can be improved by ants system using a genetic algorithm which adapts the ant control parameters to the search process [Barpanda2011] [Lee2008] [White1998]. Hong Ngo applied an ant algorithm in WDM optical networks for solving the dynamic routing and wavelength assignment problem under the wavelength continuity constraint and update the routing table accordingly and used a small number of agents to reduce the setup delay [Ngo2006].

The above mentioned approaches and algorithms have been many advantages, however, they lack in terms of full utilization of the network capacity and high setup time. Since the problem of survivable routing is a route optimization problem and in an attempt to take profit from their advantages and avoid their weaknesses, we apply the latest swarm based nature inspired Intelligent Water Drop (IWD) technique in routing problem which has been developed by Shah Hosseini [Hosseini2007]. IWD by its inherent nature is capable to solve routing problems and converging to the shortest path tour in reasonable period of time. In various problems, this algorithm has been already applied successfully to many combinatorial problems such as Travelling Salesman Problem (TSP) and multiple knapsack problem [Hosseini2008], vehicle routing [Booyavi2014], automatic generation of test data [Srivastava2012a], optimal data aggregation tree [Hoang2012] and scheduling problems where it has been shown that it is competitive to other meta-heuristic algorithms. However, IWD based techniques is not attempted to solve the survivable lightpath routing and wavelength assignment problem in dynamic WDM network through natural phenomenon of swarms of intelligent water drops agent to find lightpaths..

Intelligence techniques could provide some better performance results than the traditional routing algorithms as the latter do not seem to be adequate to tackle the increasing complexity in network. Depending on the problem, one technique may perform better than the other. GA is a population based approach that uses the genetic operators to derive the fitness function and calibrate the efficient solutions. But, there are some demerits like the external optimization in the GA that provides a single solution where the local optimum can be modified for the worst cases rather than the global optimum, which makes the result less stable. In GA based approach increasing mutation rate itself is a big problem. Results of this approach are unstable as it suffers from local optima problem [Agarwal2012]. The ABC algorithm is a population-based evolutionary, stochastic method that can be implemented on a wide range of problems, including global optimization. It's also a type of swarm intelligence algorithm for the same. In this approach solution is available only when bees complete its exploration. Current group of bees cannot proceed further till all bee return to nest. Each bee requires remembering the current intermediate status of network explorations, which is exchanged among other bees, hence, complexity and overhead increases. Bee algorithm is less adaptive than ACO [Chikhalikar2013]. ACO shows the behavior of the ants which is based on the randomization of the ant behavior. Tuning of the control parameters that are involved in ACO makes it more complex. In ACO based approach the pheromone updating process creates substantial overhead in generating the optimized process. It is mainly sequential process based approach because of this the solution selection is done only at the end.

ACO techniques comes up with some disadvantages like constant pheromones deposition on the edges, irrelevance of the velocity of ants in further iterations, inability of the ants to change the amount of pheromones on the edges. All these major problems faced in ACO can be removed using IWD algorithm due to its dynamic behaviour. In contrast to ACO, IWD changes the amount of soil on the edges, which ensures its dynamic behavior [Agarwal2012]. In addition, IWD can both remove and add soil to an edge, whereas these changes could not be done in the ACO algorithm. In contrast to ACO where each ant deposits a constant amount of pheromone on the edges, the changes made in the soil of an edge are not constant in the IWD algorithm. Besides, while flowing down a path the IWDs carry some soil along with them from the path, this leads to a change in the velocity of the IWDs, which is constant in ACO [Hosseini2009]. This shows the dynamic behaviour of IWD and ensures greater efficiency than various other techniques specified.

In this work we consider the problem of survivable routing in dynamic WDM networks with single link failure model based on IWD algorithm under wavelength continuity constraint. Our concerns are to develop IWD based intelligent routing algorithm with efficient search scheme that improves the performance effectively. This adaptive survivable routing mechanism inspired from the swarm of water drops that use probabilistic decision, driven by soil and did not require global information of the state of the networks during the route selection which other adaptive survivable routing approaches require.

5.2 Intelligent Water Drops (IWD) Algorithm

Intelligent water drop algorithm is a new swarm-based bio-inspired optimization algorithm which is inspired by intelligence observed in the natural water drops in the river. This optimization technique has been first introduced and proposed by Shah-Hosseini in 2007. As observed from natural river water, water drops of river move towards the center of the earth due to the effect of gravitational force which acts on it. Water drops follow the straight and shortest path towards its destination if there would have been no hindrance in the environment under the enforcement of the gravitational force. Basic IWD is shown diagrammatically in Figure 5.1. The flowing water of river obtains the optimal path under the ideal conditions as observed from the behavior of water drops. However, when water drops move it remains either under the influence of the easiness of the path or the opportunity. In the IWD algorithm, several artificial agents of water drops cooperate in order to change their environment in a way to reveal the optimal path. Revealed optimal path is the one which has the lower soil on paths. The solutions are gradually and incrementally constructed by the Intelligent Water Drops algorithm [Hosseini2009]. Consequently, the IWD algorithm is generally a constructive population-based optimization algorithm.

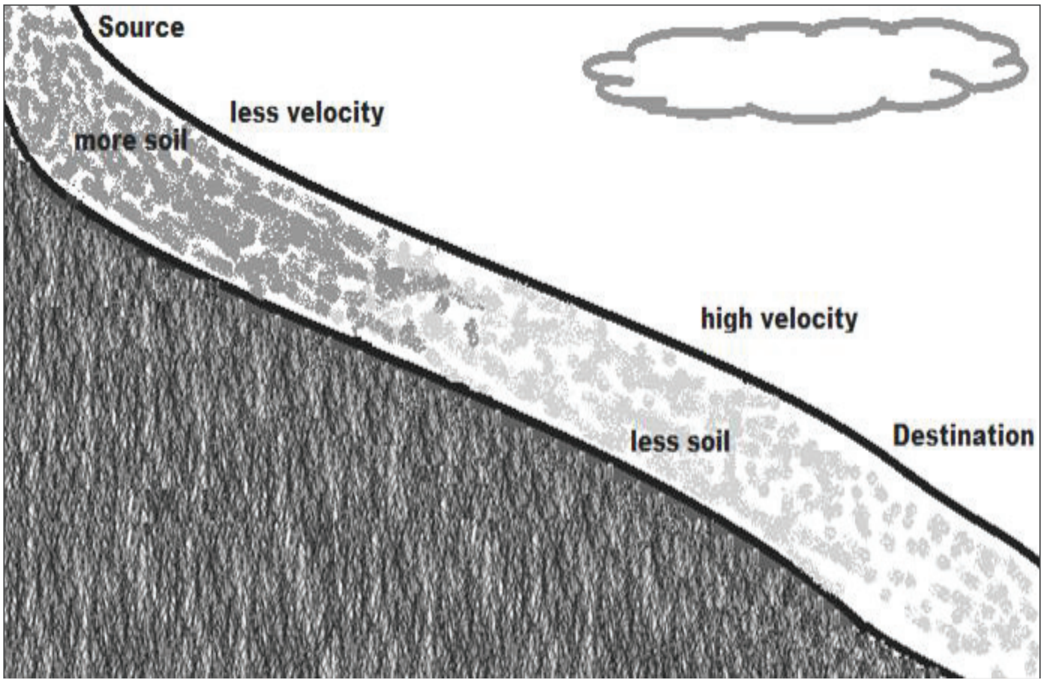


Figure 5.1: Diagrammatic Representation of IWD [Srivastava2012b]

The natural river consists of a swarm of water drops whose behavior is stimulated to find the best optimal paths between a node pair. These optimal paths follow from actions and reactions occurring among the water drops and the water drops with their riverbeds. Natural intelligent water drops have few important properties which are affected by its flow. The key prominent properties of a water drop flowing in a river are as follows:

- First is the velocity of water drop with which it is moving in the riverbeds, considered as Vel_{iwd} or Velocity (IWD).
- Secondly, each water drop of river carries an amount of soil which is represented by $Soil_{iwd}$ or Soil (IWD).

Therefore, the imaginary natural water drop transfers an amount of soil from one point to next point of a river. During its journey of transition from one place to another place the following changes occur:

- The velocity of natural water drop increases.
- Contents of the soil of the water drop are also increased.
- The amount of soil of the river's bed between one points to next point is decreased.

Flowing water drop collects an amount of soil of the river’s bed within it. The velocity of the water drop is increased during the transition and collects more soil. The velocity of water drop has an important role in removing soil from the bed of the river. When the velocity of a flowing water drop is higher, then it collects more soil within it, in comparison to a water drop with lower velocity [Hosseini2007] [Hosseini2009]. The velocity of the water drop increases more on a path which has less amount of soil then a path with a higher amount of soil. The IWD usually prefers the paths having low soils rather than the paths having high soils. A water drop usually chooses the easiest path when several paths exist in the front of a water drop.

From the current location to the next location velocity of IWD, Vel_{iwd} is increased by an amount, which is nonlinearly proportional to the inverse of the amount of soil between the two locations, referred to as the change in velocity. The soil of IWD, $Soil_{iwd}$ is increased by extracting some soil of the path between two locations. The amount of soil which is deposit to the IWD, is inversely proportional to the time needed for the IWD to pass from its current node to next node. IWD always prefers to choose the path with lesser amount of soil contents. Environment contains lots of path from source to destination [Duan2008] which may be known or unknown. IWD follows the best path to reach the destination (best is in terms of cost or any other desired metrics) when destination is known. In case destination is unknown, IWD finds the optimal destination.

Several artificial water drops affect the surrounding environment as they move through the river bed in the way towards the final destination. This flowing towards destination is caused by the gravitational force of the earth. In the water drops path, if there are no obstacles or barriers, then water drops would follow a direct path toward the destination. Obviously, it is the shortest path from the starting source place to the destination. In reality there are lots of twists and turns and other types of obstacles or barriers in the path of river, so the real path may be therefore different from the ideal one. The constructed paths by the water drop sounds to be optimum one with respect to the distance from the destination as well as the environment constraints [Duan2008]. The IWD selects a path based on probabilistic function. The IWD algorithm uses a parameterized probabilistic model to construct solutions. In order to increase the probability of constructing a better solution quality, values of the IWDs parameter are updated.

5.3 System Model and Mathematical Formulation

We assume that a given optical network topology is represented by a graph G(N,E,W) which consists of a set of nodes N = {1.....N }, set of edges E = {1......E} and set of wavelengths on each link W = {1......W} , where it has an edge (i, j) when a link between node i and node j exist. Each fiber supports same W wavelengths on each link of a fiber.

A mathematical model for the considered problem is formulated in this section so as to maximize the network throughput as well as to minimize the network resources utilized in the establishment of connection requests in a wavelength-routed WDM optical network.

Various notations used in the formulation are as follows:

Input parameters

N: Maximum number of nodes in the network

E: Set of edges in the network, where (i,j) is in set E.

W: Maximum number of wavelengths channels on a link .

R: Set of lightpath requests between a source and destination pair.

s: Source node

d: Destination node

(i,j): Link between node i to node j

Binary decision indicator variable

$$\gamma^{p,(s,d)} = \begin{cases} 1, & if\ primary\ lighpath\ p\ for\ a\ node\ pair\ (s,d)\ is\ established \\ & \quad in\ network \\ 0, & otherwise \end{cases}$$

$$\gamma^{b,(s,d)} = \begin{cases} 1, & if\ backup\ lightpath\ b\ for\ a\ node\ pair\ (s,d)\ is\ established \\ & \quad in\ network \\ 0, & otherwise \end{cases}$$

$$\gamma_{\omega}^{p,(s,d)} = \begin{cases} 1, & if\ primary\ lightpath\ p\ for\ node\ pair\ (s,d)\ is\ established \\ & \quad using\ wavelength\ \omega \\ 0, & otherwise \end{cases}$$

$$\gamma_{\omega}^{b,(s,d)} = \begin{cases} 1, & if\ backup\ lightpath\ b\ for\ node\ pair\ (s,d)\ is\ established \\ & \quad using\ wavelength\ \omega \\ 0, & otherwise \end{cases}$$

$$\gamma_{(i,j)}^{p,(s,d)} = \begin{cases} 1, & if\ primary\ lightpath\ p\ for\ node\ pair\ (s,d)\ uses\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\gamma_{(i,j)}^{b,(s,d)} = \begin{cases} 1, & if\ backup\ lightpath\ b\ for\ node\ pair\ (s,d)\ uses\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\gamma_{\omega,(i,j)}^{p,(s,d)} = \begin{cases} 1, & if\ primary\ lightpath\ p\ for\ node\ pair\ (s,d)\ is\ established \\ & using\ wavelength\ \omega\ over\ a\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\gamma_{\omega,(i,j)}^{b,(s,d)} = \begin{cases} 1, & if\ backup\ lightpath\ b\ for\ node\ pair\ (s,d)\ is\ established \\ & using\ wavelength\ \omega\ over\ a\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

$$\gamma_{\omega,(i,j)}^{bm,(s,d)} = \begin{cases} 1, & if\ backup\ lightpath\ b\ for\ node\ pair\ (s,d)\ is\ multiplexed \\ & with\ an\ existing\ backup\ lightpath\ over\ \omega\ on\ link\ (i,j) \\ 0, & otherwise \end{cases}$$

5.3.1 Objective Function

The two objectives considered are as follow:

- Minimize the network resource used by connection request in the network

$$\text{Minimize} \left(\sum_{\omega=1}^{|W|} \gamma_{\omega,(i,j)}^{p,(s,d)} + \sum_{\omega=1}^{|W|} (\gamma_{\omega,(i,j)}^{b,(s,d)} - \gamma_{\omega,(i,j)}^{bm,(s,d)}) \right),\ \forall (s,d) \in N, (i,j) \in E, p, b \in R \quad (5.1)$$

- Maximize the number of lightpath request established in the network

$$\text{Maximize } (\sum_{p=1}^{|R|} \gamma^{p,(s,d)}),\ \forall (s,d) \in N \quad (5.2)$$

Constraints

Above objective functions are subject to the following constraints:

- Flow conservation for primary lightpath to guarantee that the obtained solution is a valid path from source *s* to destination *d*.

$$\sum_{j\in N}\gamma_{(i,j)}^{p,(s,d)} - \sum_{j\in N}\gamma_{(j,i)}^{p,(s,d)} = \begin{cases} 1 & if\ i=s \\ -1 & if\ i=d \\ 0 & if\ i\notin (s,d) \end{cases} \tag{5.3}$$

- Flow conservation for backup lightpath to guarantee that the obtained solution is a valid path from sources s to destination *d*.

$$\sum_{j\in N}\gamma_{(i,j)}^{b(s,d)} - \sum_{j\in N}\gamma_{(j,i)}^{b,(s,d)} = \begin{cases} 1 & if\ i=s \\ -1 & if\ i=d \\ 0 & if\ i\notin (s,d) \end{cases} \tag{5.4}$$

- The number of the wavelength used on a link (i,j) cannot be more than the maximum number of available wavelength channels on the link.

$$\sum_{\omega\in W}\gamma_{\omega,(i,j)}^{p,(s,d)} + \sum_{\omega\in W}\gamma_{\omega,(i,j)}^{b,(s,d)} \leq \text{W}, \forall\ \text{p,b} \in \text{R}_\text{n} \tag{5.5}$$

- Wavelength continuity constraint ensure that a lightpath consist of the same wavelength across all the traversed links.

  For primary lightpath demands

$$\sum_{\omega\in W}\gamma_{\omega}^{p,(s,d)} \leq 1,\ \forall\ \text{p}\in\text{R}, (\text{s},\text{d})\in\text{N} \tag{5.6}$$

  For backup lightpath demands

$$\sum_{\omega\in W}\gamma_{\omega}^{b,(s,d)} \leq 1, \forall\ \text{b}\in\text{R}, (\text{s},\text{d})\in\text{N} \tag{5.7}$$

- Distinct wavelength constraint ensures that no two primary lightpath request is assigned an identical wavelength, when traversing through the same link (i, j).

$$\sum_{p}^{|R|}\gamma_{\omega,(i,j)}^{p,(s,d)} \leq 1,\ \forall\ \omega\in\text{W}, (\text{s},\text{d})\in\text{N}, (\text{i},\text{j})\in\text{E} \tag{5.8}$$

- Primary and backup lightpath disjoint constraint ensures that both lightpaths cannot use the identical link for a connection request.

$$\gamma_{(i,j)}^{p,(s,d)} + \gamma_{(i,j)}^{b,(s,d)} \leq 1, \forall\ \text{p},\text{b}\in\text{R}, (\text{s},\text{d})\in\text{N}, (\text{i},\text{j})\in\text{E} \tag{5.9}$$

- Primary and backup lightpath cannot be assigned same wavelength channel on the same link.

$$\gamma_{\omega,(i,j)}^{p,(s,d)} + \gamma_{\omega,(i,j)}^{b,(s,d)} \leq 1, \forall\ \omega\in\text{W}, \text{p},\text{b}\in\text{R}, (\text{s},\text{d})\in\text{N}, (\text{i},\text{j})\in\text{E} \tag{5.10}$$

- With backup multiplexing, if a new backup lightpath uses the same channel on a link (i, j) as an existing backup lightpath then no extra resource is required on that link.

$$\gamma_{\omega,(i,j)}^{b,(s,d)} - \gamma_{\omega,(i,j)}^{bm,(s,d)} \geq 0\ ,\ \forall (i,j) \in E, (\mathrm{s},\mathrm{d}) \in \mathrm{N}, \omega \in \mathrm{W} \qquad (5.11)$$

Here, we have been considered the problem of survivable routing in WDM network for dynamic traffic using IWD algorithm. For the dynamic arriving connection demands, our objective is to maximize the network throughput i.e. the number of established lightpath connections in the network and minimize the network resources in the establishment of connection requests in a wavelength-routed WDM optical network. We are mainly concerned with dynamically determining the link disjoint paths between a node pair to establish a dependable lightpath with backup sharing such that it satisfies the above problem constraint to achieve the problem objectives.

5.4 Intelligent Water Drops Algorithm for Survivable Routing

The operational functional design of the proposed IWD based survivable RWA is demonstrated in Figure 5.2. This functional architecture has four broad components, path selection and bandwidth allocation mechanism, IWDs parameter set, IWDs flow mechanism and routing decision information. These four components interact and collaborate closely with network status information in the decision process for the solution of the problem.

IWDs flow mechanism functionality ensure that IWD explores all possibilities of the next forward moves from source to destination. It governs the rule of movement of artificial water drops agent to next node. It decides to which next transition node, the movement will take place. The movement of IWDs performed in discrete finite length time steps for arriving traffic demands. The IWDs chooses a path based on a probabilistic function which is shown in equation 5.12. In the process of exploration of the network, each IWDs maintain its own private parameter data set and the values of these parameters are updated. This set may consist of bandwidth resource and its availability, route length and cost status information etc. within IWDs. For each arriving incoming demands at a source node, IWDs moves to next forward node according to the selection probability which is computed and updated on visiting various nodes. This decision taken based on routing information available as probabilistic selection value of soil parameter. A node which has the highest selection probability among all the unvisited neighboring nodes is chosen as next node to transmit further. The same process is applied at the next nodes until it reach to the destination node. When IWDs terminates at desired destination node, an optimal path for the connection request is determined and channel bandwidth assignment process is take place. In proposed IWD based survivable routing, network node has probabilistic soil value that contains the selection probability of neighboring node when an IWD move towards its destination node. IWD is launched from each source node to the desired destination. In the soil content, algorithm ensures that the dynamic information about network resource, cost, length, and congestion is well reflected. The path for an incoming connection request is computed based on the highest selection probability of soil content at links, thus the setup time may be reduced. IWD based algorithm outperforms in performance as intelligent water drops agent can efficiently explore the latest network state dynamically.

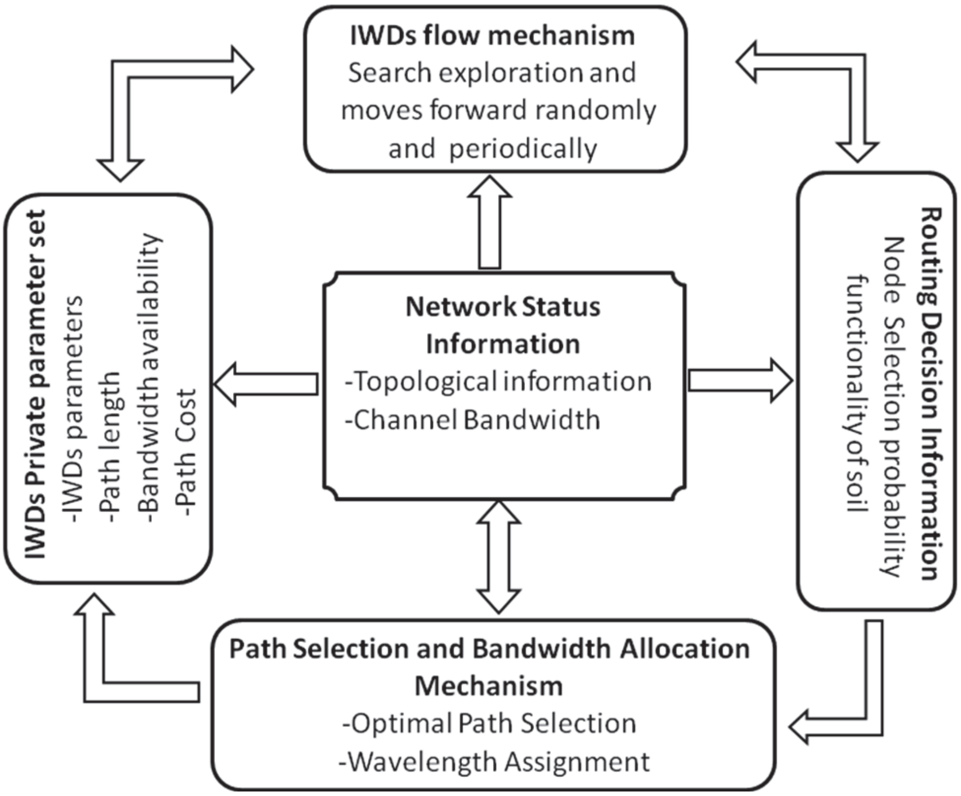


Figure 5.2: Functional Design of Proposed IWD based Survivable RWA

5.4.1 Proposed IWD based Survivable Routing Algorithm

An intelligent water drops algorithm is applied to survivable routing and wavelength assignment problem in wavelength routed wavelength division multiplexed optical networks. Using intelligent water drop based algorithm, lightpaths are intelligently determined considering the dynamic behavior of network such that a single link failure would not disconnect and disrupt the network traffic. IWD is a nature-inspired optimization algorithm inspired from the natural water drops which change their environment to find the near optimal or optimal path to their destination. The processes that happen between the water drops of a river and the soil of the river bed formed the basis for this algorithm.

Each IWD at a source node starts constructing its solution gradually by traversing on the nodes of the graph along with its edges until IWD completes its solution finally. Hence, every artificial water drop determines its flow path which is a feasible optimal solution of the problem. Algorithm completes one iteration step when all IWDs have been completed their solutions. When each iteration step completes, the iteration best solution set T_{IB} found and it is used to update the total best T_{GB} solution. The amount of soil on the edges of the iteration-best solution T_{IB} is reduced based on the quality of the solution. Afterward, repeat the algorithm again using another IWD on the graph with same status of soils and the algorithm stops when termination condition such as a defined number of iterations or destination node is reached. IWD algorithm determines best quality of solutions. The complete logical process of the algorithm is explained by a flow chart shown in Figure 5.3. The IWD algorithm is modified to solve the survivable routing problem in WDM network as shown in Algorithm 5.1 and whose steps are elaborated below in detail.

Detail of proposed algorithm is described below.

Initialization of the static parameters

These parameters are initialized with static values, and they remain unchanged during the search process.

- Velocity updating parameters (a_v, b_v, c_v): These are used to control velocity update function. As per the need of the problem, values of these defined configuration parameters can be decided. For the current problem values of these parameters are initialized as: $a_v = 1$, $b_y = 0.1$, $c_v = 1$.
- Soil updating parameters (a_s, b_s, c_s): These are used to control soil update function. For the current problem values of these parameters are initialized as: $a_s = 1$, $b_s = 0.1$, $c_s = 1$.
- Local soil updating parameter ($\propto_{ls}$): Its value is initialized as $\propto_{ls} = 0.1$. Its value can be in between 0 and 1 according to the amount of soil on the links.

- The initial soil on each link is given by the constant *InitialSoil*. Initially, all of the link's soil of network topology is initialized to *InitialSoil* value, i.e. $\text{Soil}_{i,j}$= *InitialSoil,* ∀ i, j. Value of *InitialSoil* parameter is initialized to a value of 1000.
- The initial velocity of each IWD is denoted by constant *InitialVe*l; *InitialVel* is set to 100.

Initialization of the dynamic parameters

These parameters are initialized at the beginning of the search and are updated during the search process.

- The visited node list of every IWD, which denoted by V_{iwd}^{list} , is initially set to empty,
- Initially, set the velocity of each IWD to same *InitialVel* value.
- Initially, set the soil of each IWD, $Soil_{iwd}$, to the zero amount of soil.
- Initially set to empty, a tabu list, which maintains links or nodes which violate environment constraint of the current problem.

Selection of the next node

Each IWD, which is present at node i is supposed to move to the next node j from the current node in the network topology. Node j is chosen from the list of its neighboring nodes, ignoring the node which were already visited according to probabilistic selection probability, $P_{iwd}\ (i,j)$, which is inversely proportional to the amount of soil on the link's edge as follows:

$$P_{iwd}\ (i,j) = \frac{f(Soil_{i,j})}{\sum_{n \notin \mathrm{V}_{\mathrm{iwd}}^{\mathrm{list}}} f(Soil_{i,n})} \tag{5.12}$$

where,

$$f(Soil_{i,j}) = 1/[\varepsilon_s + g(Soil_{i,j})] \tag{5.13}$$

here, ε_s is a small positive number which is taken in order to prevent any possibility of division by zero error. Here, value of constant ε_s is assumed to be 0.001 which ensures that equation has no division by zero problem.

$$g(Soil_{i,j}) = \begin{cases} Soil_{i,j}\ , & when\ min_{m \notin \mathrm{V}_{\mathrm{iwd}}^{\mathrm{list}}}(Soil_{i,m}) \geq 0 \\ Soil_{i,j} - min_{m \notin V_{\mathrm{iwd}}^{\mathrm{list}}}(Soil_{i,k}), & elsewere \end{cases}$$

(5.14)

Updation of velocity

Each IWD's velocity, Vel_{iwd} , which moves from node i to node j is updated as:

$$Vel_{iwd}\,(t) = Vel_{iwd}\,(t-1) + {}^{a_v}\!/\![b_v + c_v * \ Soil_{i,j}\,] \tag{5.15}$$

where, $Vel_{iwd}\,(t)$ is the updated velocity of the IWD.

Computation of delta soil

Soil amount, $\Delta\, Soil_{i,j}$, is computed for each IWD that is moving on traversed path from node i to node j, which is loaded from the edge link (i,j) between node i to node j as:

$$\Delta\, Soil_{i,j} = {}^{a_s}\!/\![b_s + c_s * \ Time_{i,j}(Vel_{iwd}\,)] \tag{5.16}$$

where,

$$Time_{i,j}(Vel_{IWD}) = \mathrm{HUD_{SR}}\,(\mathrm{i,j})/\max(\tau_v + Vel_{IWD})$$

A small positive number τ_v i.e. τ_v=0.001, is taken to guarantee that equation did not have any possibility of division by zero error problem. Soil that the IWD can carry depends on the velocity of IWD i.e. on the resources of its path edge.

The heuristic undesirability $\mathrm{HUD_{SR}}\,(\mathrm{i,j})$ function for our problem is defined as

$$\mathrm{HUD_{SR}}\,(\mathrm{i,j}) = \begin{cases} C^{i,j} + \dfrac{(\mathrm{W}_t^{i,j} - \mathrm{W}_f^{i,j} + 1)}{W_t^{i,j}} & \text{for primary route} \\ C^{i,j} + \dfrac{(\mathrm{W}_t^{i,j} - (\mathrm{W}_f^{i,j} + \mathrm{W}_{bs}^{i,j}) + 1}{W_t^{i,j}} & \text{for backup route} \end{cases} \tag{5.17}$$

where $\mathrm{W}_t^{i,j}$ and $\mathrm{W}_f^{i,j}$ is the total available wavelength channels on link (i, j) respectively and $\mathrm{W}_{bs}^{i,j}$ is already used assigned wavelength channels for backup lightpaths on the link (i ,j) and $C^{i,j}$ is the defined hop cost of edge between node i to node j of the network topology. In the simulation of our work we set the value of $C^{i,j}$ =1. The equation (5.17) shows that $\mathrm{HUD_{SR}}\,(\mathrm{i,j})$ function decreases if the number of free channel resources is less and edge cost is high while it increases when edges have high resources and low hop cost. Hence, among the edges that can be selected for next move of IWD is the edge that has more available spare resources and has low hop cost is more desirable. Soil that the IWD can carry depends on the velocity of IWD i.e. on the network resources of its path edge.

Updation of edge soil

During the transition to next nodes and while selecting edges, the IWD updates the soil carried by itself and removes some soil from the currently used edge.

For each IWD, when an IWD moves from node i to node j, updates of the value of edge soil $Soil_{i,j}$ traversed by that IWD between nodes i, j and soil that loads within IWD $Soil_{iwd}$ takes place as follows:

$$Soil_{i,j} = (1 - \propto_{ls})\, Soil_{i,j} - \propto_{ls} * \Delta\, Soil_{i,j} / [N_{nodes} - 1] \tag{5.18}$$

where $\propto_{\mathrm{ls}} \in [0,1]$ is local soil updating parameter whose value can be $0 \leq \propto_{\mathrm{ls}} \leq 1$ and N_{nodes} is the number of node in traversed path by that IWD.

Updation of IWDs soil

Update the soil content of the IWD, $Soil_{iwd}$, when IWD is moving from node i to node j as follows:

$$Soil_{iwd} = Soil_{iwd} + {}^{\Delta\, Soil_{i,j}}\!\Big/_{[N_{nodes} - 1]} \tag{5.19}$$

Here $\mathrm{N_{nodes}}$ is the number of nodes in the path traversed by that IWD to reach the destination through node j. When the number of nodes is more, very little amount of soil is removed from edge, which ensures to explore the search for routes with less number of nodes. So, when explored path is larger in length than less amount of soil will be removed from the link of that route which ensures the exploration to visit towards the most feasible path that has minimum path length. Above updates work as a learning mechanism which will be used to guide the IWDs towards the solution of higher goodness quality in the moves of next generation. Gathered information by this updating process as well as other ones, controls the algorithms intensification and diversification towards the best optimal solution.

Evaluation of each solution in IWD

An edge with less soil allows IWD to gain more speed than an edge with more soil. When all the IWDs complete the exploration, a local evaluation is performed to the solution constructed by each IWDs to check the quality of solution. For each IWD the goodness quality i.e. objective fitness of IWD is required to be evaluated for each solution constructed with respect to the constraints of the problem. The quality or goodness function is represented as $\Psi(.)$. A set of IWDs can work together and be utilized to determine the optimal solution. The IWDs which have largest fitness quality value in terms of continuous available common channels, free wavelengths and minimum hop length cost are preferably desired network parameter for the evaluation of solution constructed by swarms of IWDs. Consequently, better traversed constructed solutions have the possible chance of visiting by other IWD in the next iterations and leads to the convergence of optimal solution for global best one. The IWDs determined path is rich in resources and minimum in cost that satisfies the other constraint of the problem across iterations denoted by set T_{IB}. The iteration best solution is determined from all the solutions that have found by IWDs as

$$T_{IB} = \max\left(\Psi(IWDs) \right), \forall \text{ IWDs} \tag{5.20}$$

The goodness fitness function considered is

$$\Psi(IWDs) = \begin{cases} \dfrac{\psi_1}{H_{count}} + \psi_2 * \dfrac{W_{\lambda c}}{W_T} & \text{for primary path} \\ \dfrac{\psi_1}{H_{count}} + \psi_2 * \dfrac{W_{\lambda c} + W_{bs}}{W_T} & \text{for backup path} \end{cases} \tag{5.21}$$

where $W_{\lambda c}$ is available continuous free channels along route and physical length cost of route constructed by IWD respectively. ψ_1 and ψ_2 are positive weight control constant factor such that $\psi_1 + \psi_2 = 1$. In simulation each one considered equally important. In this work, considered fitness quality function is used to filter and favor such routes which have more spare resource or that have already more assigned backup network resource for protection and has shorter length to improve the network performance.

Global soil update

Soil of the path explored by IWD's iteration having best quality is included in the set of global best one denoted by T_{GB} to be updated. Soils of current iterations of best quality solution path which included in T_{IB} is updated according to equation given below:

$$Soil_{i,j} = \left(1 + \beta_{gs}\right) Soil_{i,j} - \beta_{gs} * \; Soil_{iwd}/[N_{nodes} - 1] \;\; \forall \, (i,j) \in T_{IB} \tag{5.22}$$

where β_{gs} is the global soil updating parameters whose value can be between $0 \leq \beta_{gs} \leq 1$. $Soil_{iwd}$ represent the soil of IWD when it reaches to the destination node and N_{nodes} is the number of nodes in the tour of the solution explored by the IWD. This global soil updates serve as the reinforcement of best solution gradually and thus, IWDs are directed to search near good solution in further explorations with a hope of getting optimal solution.

Update the total best solution T_{GB} by the current iteration best solution T_{IB} after each iteration

$$T_{GB} = \begin{cases} T_{IB} & if\ \Psi(T_{GB}) < \Psi(T_{IB}) \\ T_{GB} & elsewhere \end{cases} \tag{5.23}$$

where $\Psi(.)$ is a quality or objective fitness function which defines that constructed tour of IWD should have better goodness value.

When the global soil update is finished, an iteration of the IWD has ended and iteration begins with new IWDs. This process continues until defined termination condition not meets which is to reach destination node or the maximum number of iterations is met. In this manner, a number of different possible routes with varying levels of the link resources, nodes and cost are explored by each IWD and may be available for the source node to start data transmission to the destination node. However each routes obtained may not be suitable to provide similar degree of goodness quality of service path to users. The best optimal routes will be determined with their corresponding highest fitness value between given source and destination nodes. The path satisfying the desired fitness objectives are chosen as the primary path and backup path. Thus, for each arriving connection request, first setup the primary lightpath using IWD based approach and then all links of the primary path are assumed to be unavailable i.e. used in the network topology and same IWD based algorithm may be again executed to setup the backup lightpath over the remaining links of the topology. The symbol and values of major setting parameters used in our IWD algorithm for simulation are represented in Table 5.1 [Booyavi2014] [Hosseini2009] [Kayvanfar2015].

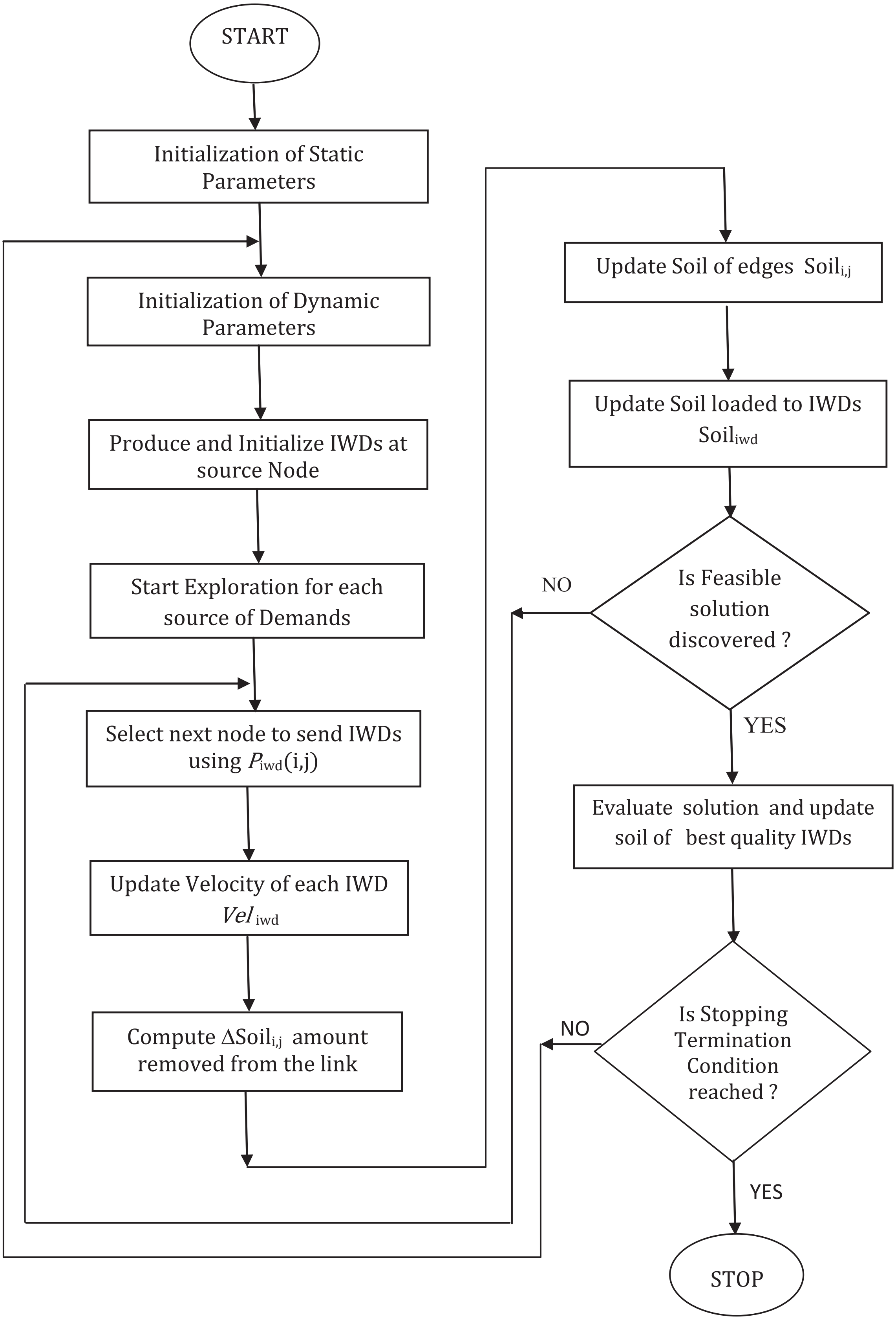


Figure 5.3: Working Phases of the IWD-SRWA Algorithm

Algorithm 5.1: IWD based Survivable Routing Algorithm

Input: Physical network topology *G*(*N*, E*,W*); Set of arriving demands R whose source node is s and destination node is d. The bandwidth requirement of each connection request is assumed to be one spare wavelength channel.

Output: Pairs of disjoint paths satisfying the problems environment constraints

---

```
begin
  Initialization of static parameters //Those parameters which do not change during the exploration process by IWDs
   set initial parameters : $a_s$, $b_s$, $c_s$. $a_v$, $b_v$, $c_v$, $\propto_{ls}$
   set initial soil on each link : $Soil_{i,j}$ = InitialSoil , $\forall i, j$
   set initial velocity parameter: $Vel_{iwd}$ = InitialVel , $\forall IWDs$
  while ( defined termination criteria has not been met ) do {
          Initialization of dynamic parameters //those parameters which change during the exploration process by IWDs
              set to empty visited node list: $V^{list}_{id}$ = { Φ}. $\forall IWDs$
              set tabu list empty which maintain constraint violations: $Tabu^{list}$ ={Φ }
              set the velocity of each IWD : $Vel_{iwd}$ = InitialVel
              set the soil of each IWD to the zero: $Soil_{iwd} = 0$
          Create and Initialize the desired IWDs at the source e node
  Update Visited node list of each IWDs and include source node as just visited node
 while ( feasible and complete solution condition not achieved) do
   for (each created IWDs) do
        For IWD at current node, i choose next node j that does not violate any given problem constraints and yet to visit by looking at the visited node list $V^{list}_{iwd}$ and $Tabu^{list}$
        Move IWD from node i to next node j on the basis of value of selection probability $P_{iwd}(i,j)$ (using Equation 5.12)
        For each IWD moving from node i to next node j update the velocity of IWD: $Vel_{iwd}$ (using Equation 5.15)
        For IWD that moving on path to node j from node i , compute soil value $\Delta Soil_{i,j}$ which IWD loads within from that traversed path (using Equation 5.16)
       Update the $Soil_{i,j}$ value of the path between edge of node i to node j (using Equation 5.18)
        Update soil that IWD loads within: $Soil_{iwd}$ (using Equation 5.19)
```

```
         for-end
         Evaluate IWDs constructed partial solutions.
         Update $V_{iwd}^{list}$ and $Tabu^{list}$
        while-end
        Evaluate and update the iterations feasible solution, $T_{IB}$.
        Update and populate total best solutions,$T_{GB}$.
        Update the global soil of best solution path (using Equation 5.22)
        while-end
        end
```

Table 5.1: Various IWDs Parameters

Parameters	Description	Value
$InitialSoil$	the initial soil of each edge	1000
$InitialVel$	the initial velocity of an IWD	100
a_v	IWD velocity updating parameters	1
b_v	IWD velocity updating parameters	0.1
c_v	IWD velocity updating parameters	1
a_s	IWD soil updating parameters	1
b_s	IWD soil updating parameters	0.1
c_s	IWD soil updating parameters	1
$Soil_{i,j}$	*Soil* on edge(i,j)	--
Vel_{iwd}	the velocity of an IWD	--
$\Delta\, Soil_{i,j}$	soil changes i.e. soil an IWD loads from an edge (i,j)	--
$Soil_{iwd}$	the soil of an IWD	--
$f(Soil_{i,j})$	the function used in the computation of $P_{iwd}\ (i,j)$	--
$g(Soil_{i,j})$	the function used in the computation of $P_{iwd}\ (i,j)$	--
$\propto_{ls}$	local soil updating parameter	0.1
β_{gs}	global soil updating parameter	0.1
ε_s	control parameter used in $f(Soil_{i,j})$	0.001
τ_v	control parameter used in computing time of an IWD along an edge	0.001
T_{IB}	Iterations Best IWDs solution	--
T_{GB}	global best IWDs solution	--
$\Psi(.)$	quality function for fitness of an IWDs solution	--
V_{iwd}^{list}	the visited node list	--
$Tabu^{list}$	Infeasible list of constraints violators	--

5.5 Simulation and Performance Analysis

This section presents the analysis of the simulation results to evaluate the accuracy and effectiveness of proposed approach for solving survivable RWA problem in WDM optical networks. The simulation of the proposed work is carried out in an environment of java in eclipse development environment through implementing program based simulation to validate the performance of the proposed approach. The functionality of the simulation architecture of chapter 2 has been followed and extended the code to implement the scenario as discussed in Figure 5.2 for the proposed algorithm. Proposed approach is evaluated and compared with Fixed Alternate routing, Adaptive shortest path routing, Ant colony and bee colony based routing algorithm [Ramaswami2002] [Ngo2006]. Fixed alternate routing algorithm pre-computes in advance a set of the shortest route between each source and destination nodes [Zang2003]. Shortest path routing algorithm computes a route between each source and destination pair of incoming demands and it considered the current status of the network state during the routing.

Three sample network topologies has considered for simulation. These typical test bench network topologies considered by research community are US network (14 Node, 24 Links) [Wang2008], USIP network (24 Nodes, 43 Links) [Venkatesh2007] and NSFNET network (14 Nodes, 21 Links) [Venkatesh2007] which are shown in Figure 5.4, Figure 5.5 and Figure 5.6 respectively. All links of the optical network topologies are assumed to have the same number of wavelengths per channel. Total number of wavelength channels per link considered for all the three test network is W=10, i.e. 10 wavelengths. Nodes do not have capabilities of wavelength conversion. We consider dynamic traffic and assume that each connection requests arrive with a random source and destination pair, one at a time. Due to the simplicity in implementation, first fit wavelength assignment heuristic for primary route and sharing backup resource concept for backup route has been used for the wavelength assignment to the lightpath demands in the proposed IWD based approach of survivable lightpath routing. When an arriving connection request is not fulfilled using the available resources of the network, it is blocked and dropped from the network. Extensive simulation experiments has performed on the test network topologies, indicate improvement in the network performance parameters. Results of simulation carried out sufficiently large number of times on each network topology and obtained results are averaged over such simulation runs for the performance evaluation. Network topologies used for simulations are shown below:

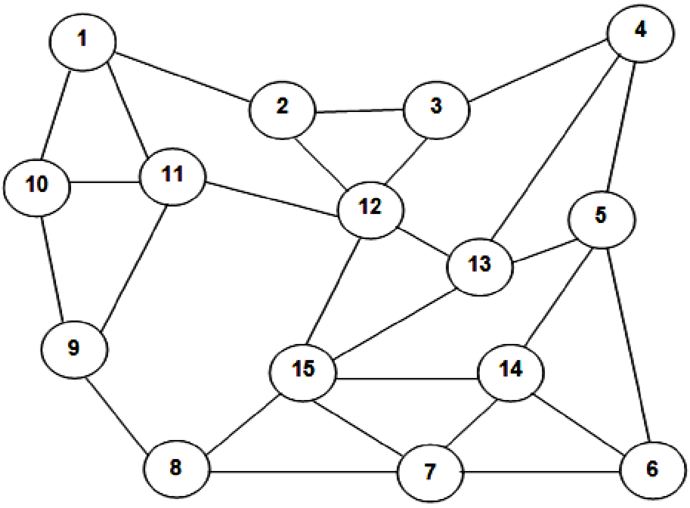


Figure 5.4: US Network Topology 1 [Wang2008]

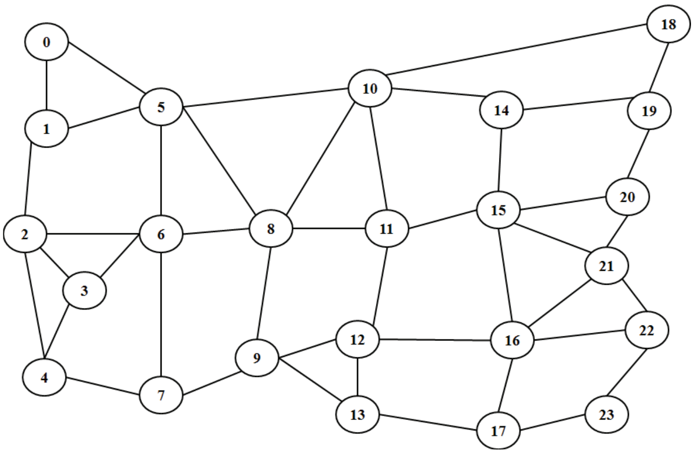


Figure 5.5: USIP Network Topology 2 [Venkatesh2007]

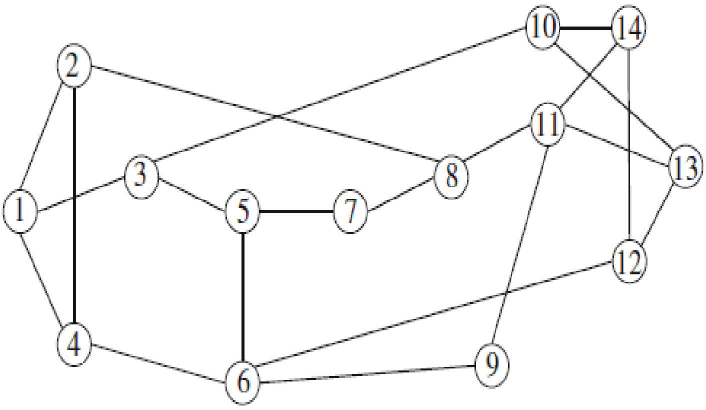


Figure 5.6: NSFNET Network Topology 3 [Venkatesh2007]

5.5.1 Investigation of Blocking Probability Performance

In this section blocking probability performance based on two network topologies has been shown in the Figure 5.4, Figure 5.5 and Figure 5.6. In the results of Figure 5.7, Figure 5.8 and Figure 5.9 comparative performance of blocking probability between IWD-SR, fixed alternate routing and shortest path routing with number of arriving lightpath requests are shown for the respective topologies. It has been shown in Figure 5.7 that the blocking probability for IWD-SR, alternate routing, and shortest path routing strategy increases as the number of incoming lightpath requests increases in the network. This behavior is attributed due to the reason of the insufficient resource availability of free wavelength channels in the network at high arrival rate of lightpath requests. When traffic load in the network is more, there will be less chance of availability of free wavelength resources for the subsequent incoming lightpath requests. Therefore, subsequent traffic of lightpath requests will be blocked. In the plotted graph, alternate routing is represented as alternate-SR and shortest path routing referred as Shortest-SR for simplicity.

Blocking probability of alternate routing is higher than the blocking probability of other two approaches. Blocking probability of IWD-SR is lowest in comparison to blocking probability of alternate routing and shortest path routing. It can be inferred from the results of Figure 5.7, Figure 5.8 and Figure 5.9 that IWD-SR provides the lower blocking probability as compared to the alternate routing and shortest path routing approach. In all the three considered network topology, it has been observed from the result that IWD based survivable routing algorithm performs better in comparison to alternate and shortest path approach for survivable WDM routing.

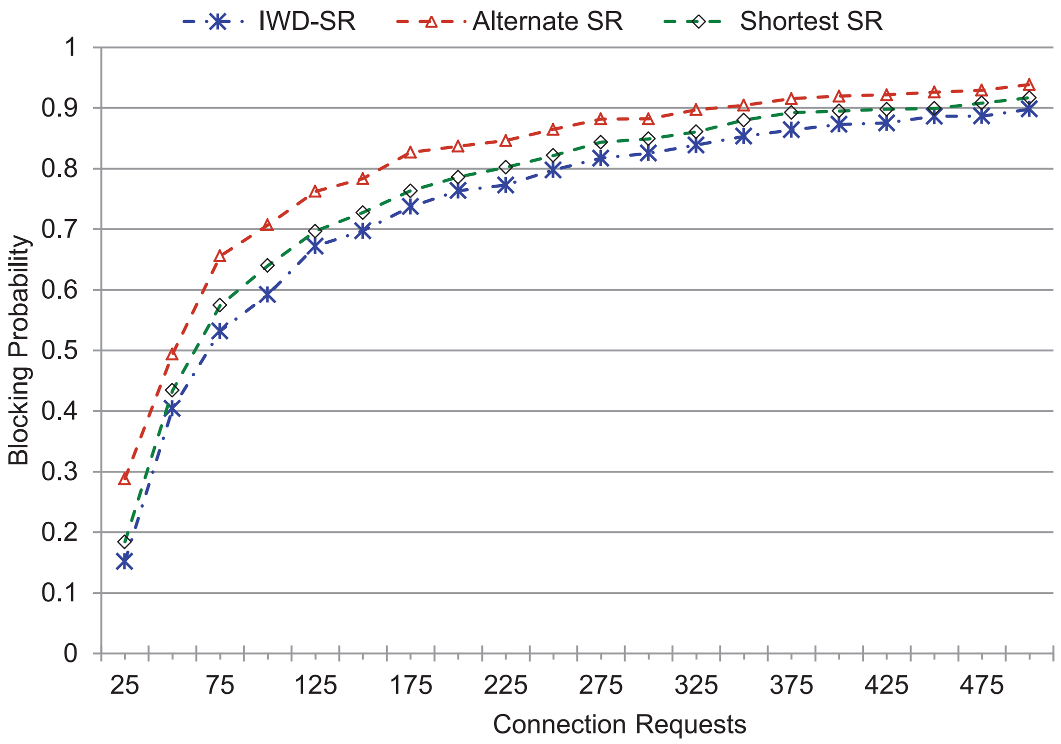


Figure 5.7: Blocking Performance on US Topology

Comparison of blocking probability performance with varying the number of wavelength channels in fiber links is shown in Figure 5.10, Figure 5.11 and Figure 5.12 for all the three considered network topologies. The number of request considered in the network is 1000 lightpath connections. The result shows blocking probability decreases with an increase in a number of channels in fiber link of the network. Thus, when number of channel is large in the network, there is better possibility of availability of free resources. Larger the number of available wavelength per fiber, lower will be the blocking probability performance of the network.

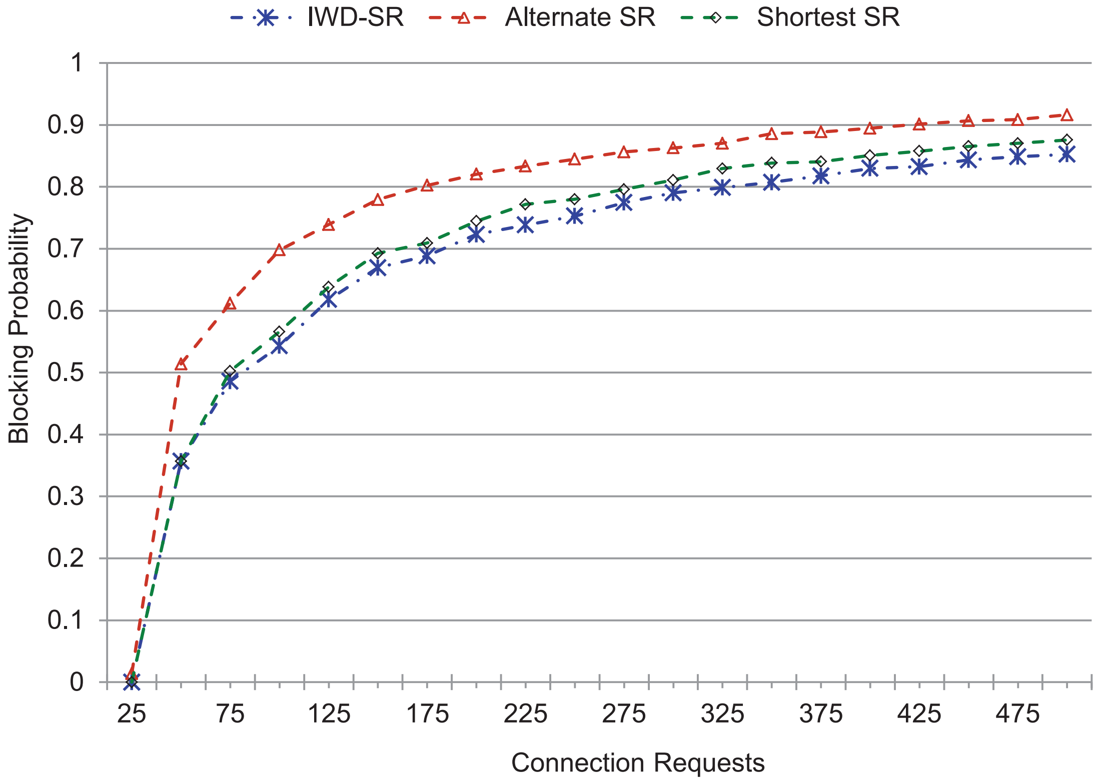


Figure 5.8: Blocking Performance on USIP Topology

It can be inferred from the figures of the result that blocking probability of the IWD-SR is better than both of the fixed alternate and shortest routing approach. It has been observed that when number of available wavelengths is more, the performance of IWD-SR algorithm is significantly better as compared to other approaches.

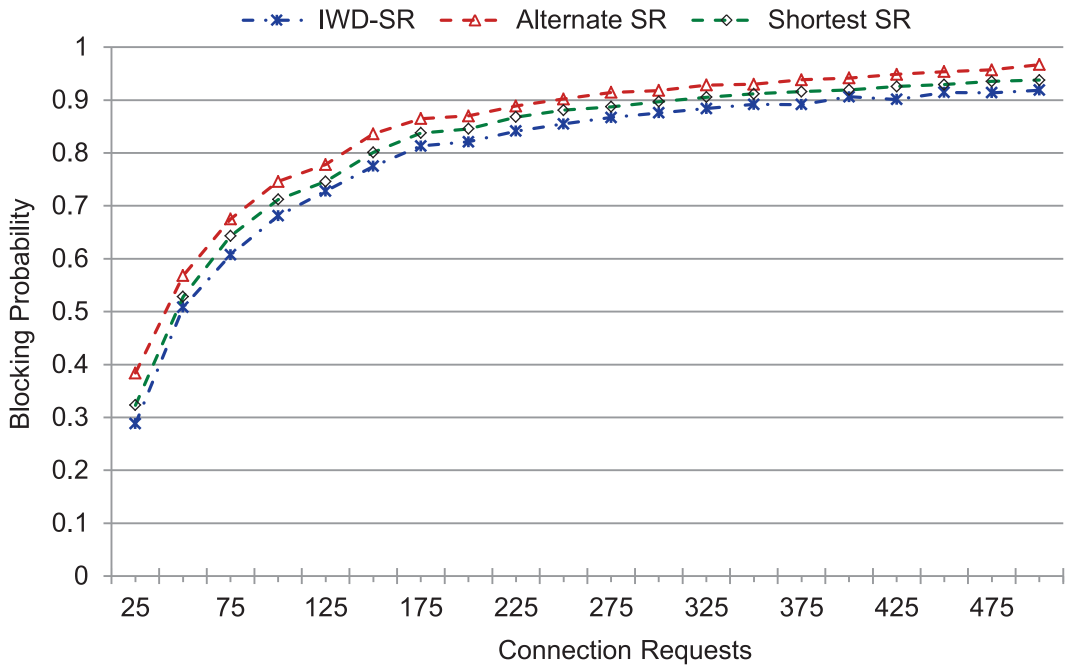


Figure 5.9: Blocking Performance on NSFNET Topology

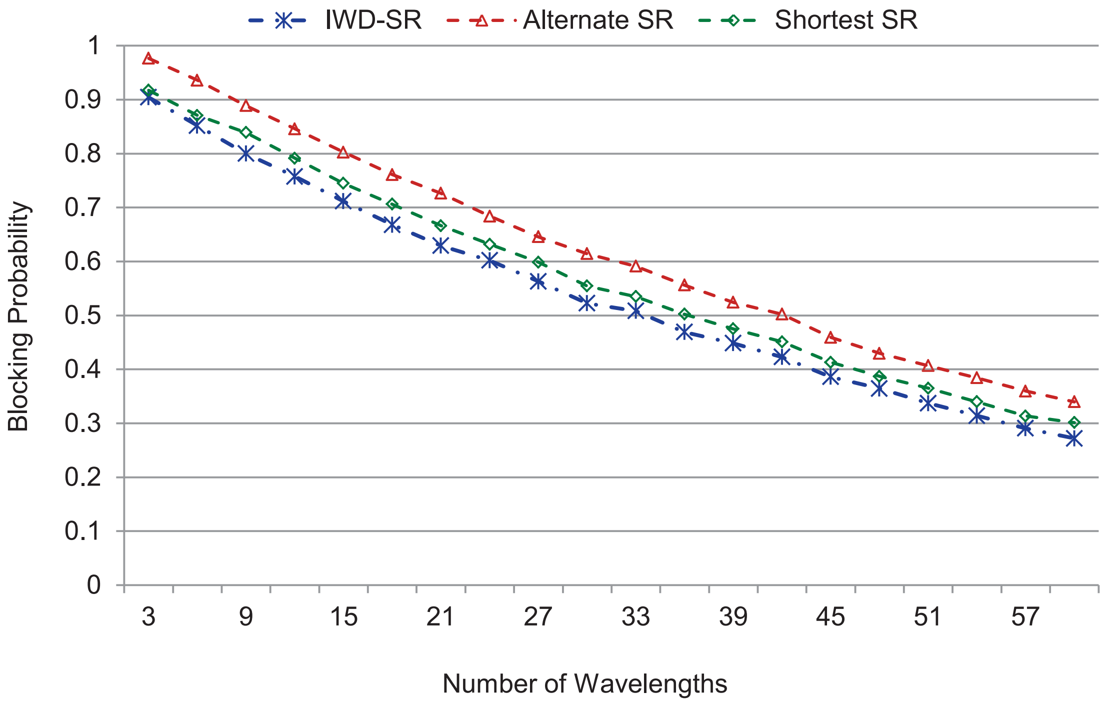


Figure 5.10: Blocking Performance vs Number of Wavelengths on US Topology

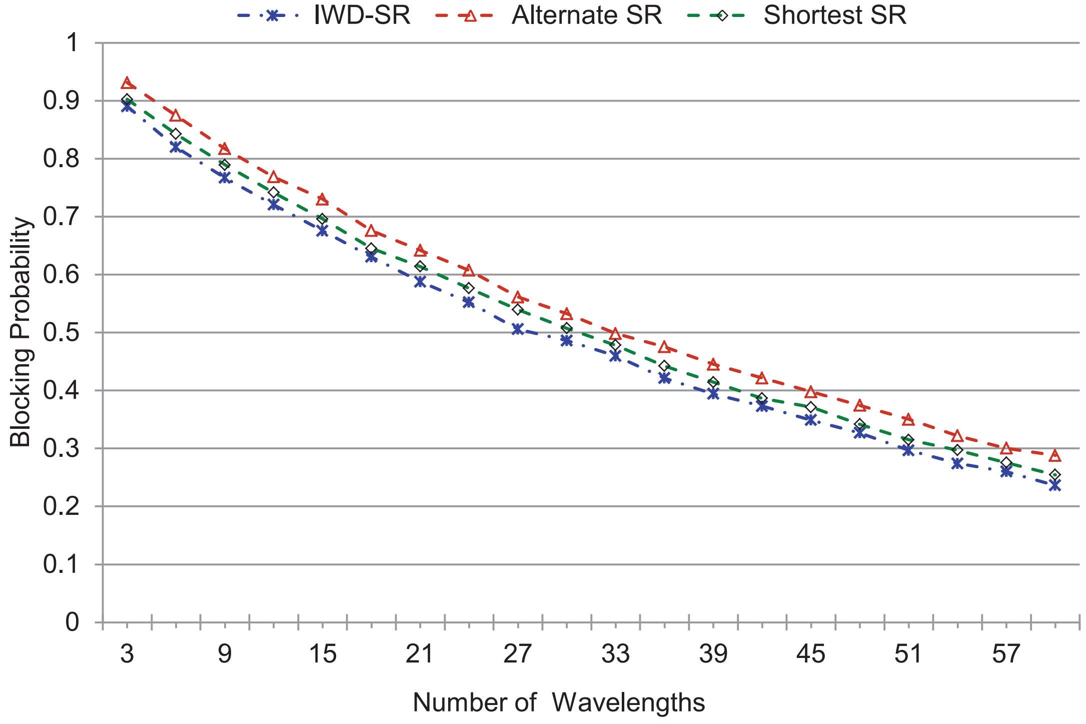


Figure 5.11: Blocking Performance vs Number of Wavelengths on USIP Topology

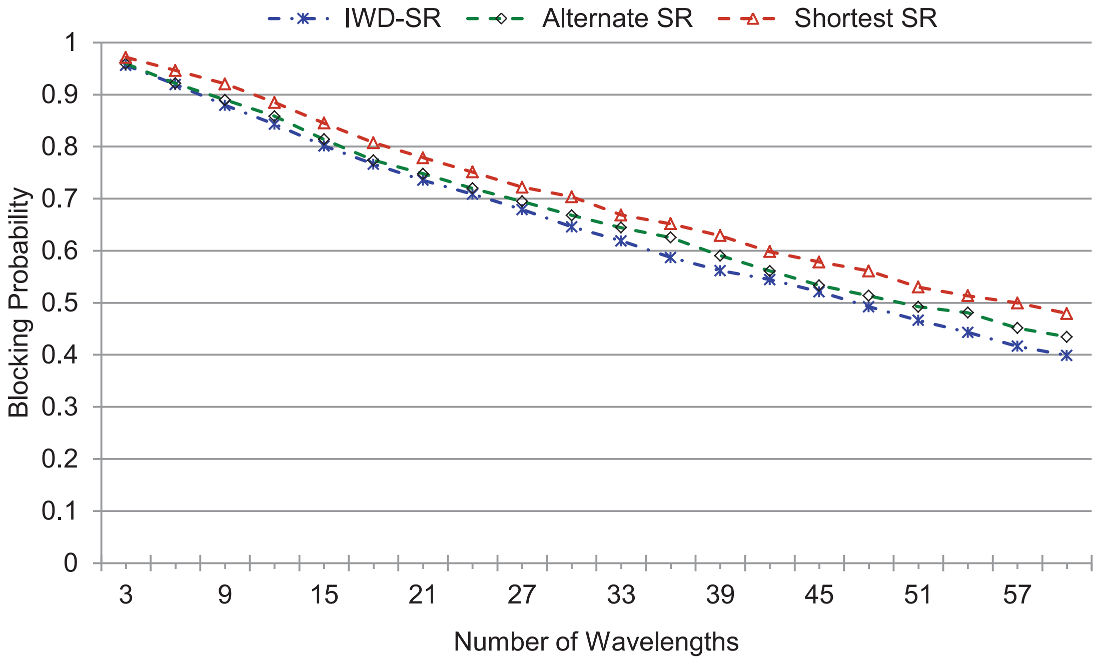


Figure 5.12: Blocking Performance vs Number of Wavelengths on NSFNET Topology

5.5.2 Investigation of Blocking Probability Improvement

In this section, we study the performance of blocking probability improvement of the IWD based survivable RWA problem on the three considered network topologies. Figure 5.13, Figure 5.14 and Figure 5.15 show the improvement benefit of the IWD based routing approach's blocking probability against shortest path routing as well as against fixed alternate routing. Figure 5.13 compare percentage improvement in the blocking probability of IWD-SR algorithm against the blocking probability of alternate and shortest path routing on US network topology.

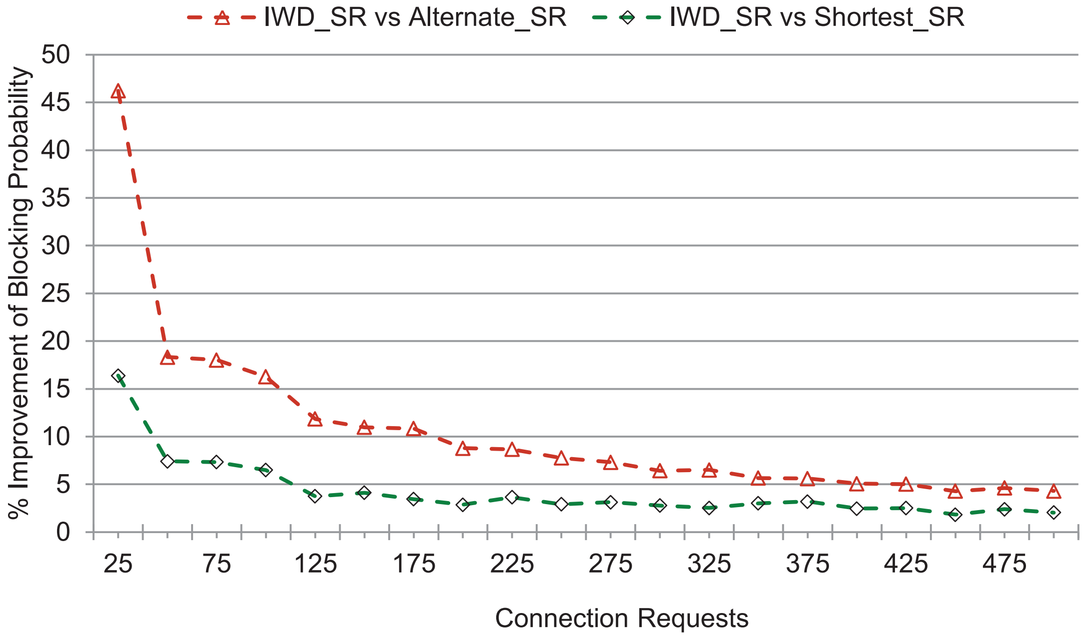


Figure 5.13: Performance Improvement of Blocking Probability on US Topology

It has been noted that the percentage improvement of blocking probability in IWD-SR is significant as compared to alternate-SR strategy when arriving lightpath requests is less but it becomes less significant at higher lightpath traffic. It is observed that percentage improvement of blocking probability decreases at the increase of incoming lightpath request in the network. With the larger number of arriving request, it becomes stable. The reason for this is that blocking probability is relatively low at lower traffic load in the network and at high traffic load blocking probability becomes high.

The result in Figure 5.13 shows that percentage improvement of IWD-SR can be as large as 46% against alternate routing and 16% against shortest path routing at low number of request. At high lightpath traffic, percentage improvement is not significantly high.

Blocking probability improvement does not increase as fast as the blocking probability increases itself with the arriving connection requests in the network. It can be observed from the results that at higher arrival rate of lightpath requests in the network, percentage improvement decreases in all the three cases. Figure 5.14 shows improvement of blocking probability of 30% to 6 % from the traffic load of 50 lightpath request against alternate routing and insignificantly very low performance improvement against shortest path routing. In Figure 5.15 blocking probability improvement of IWD based protection routing is 25% to 4% and 10% to 2% against alternate and shortest routing respectively. From results, it can be observed that percentage improvement of blocking probability does not decrease further when the number of arriving requests in the network is high. Overall observation is that the performance improvement benefits of IWD survivable routing algorithm becomes stable uniformly and does not shrink at a higher arrival rate of lightpath request. However, in our simulations result, IWD based survivable routing consistently performs comparatively better than fixed alternate routing and shortest routing in all the topologies.

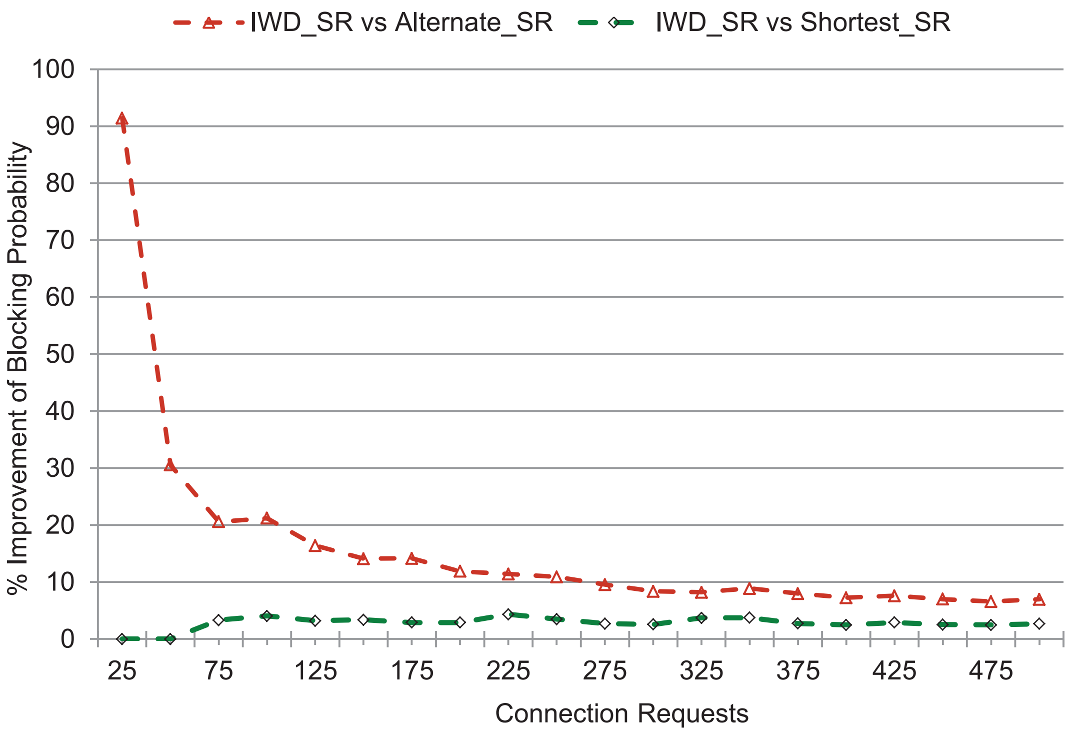


Figure 5.14: Performance Improvement of Blocking Probability on USIP Topology

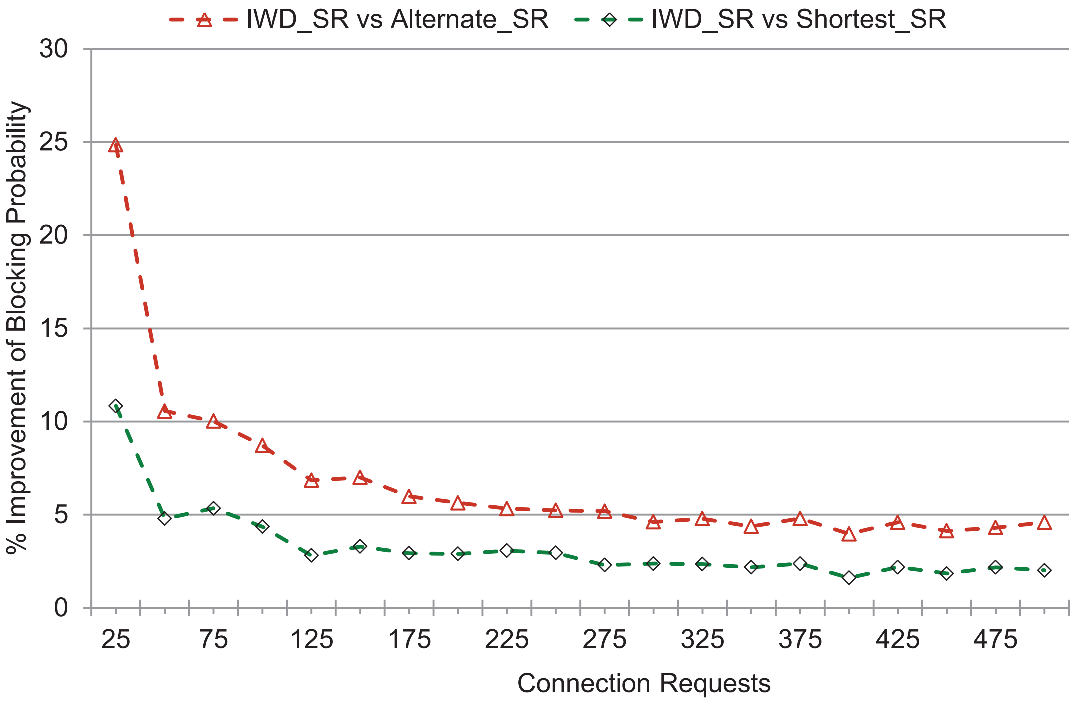


Figure 5.15: Performance Improvement of Blocking Probability on NSFNET Topology

5.5.3 Investigation of Increased Accepted Call Performance

In this section, we study the performance of Increased Accepted Call (IAC) of IWD-SR approach in comparison to alternate routing and shortest path routing algorithm. In the graph of Figure 5.16, Figure 5.17 and Figure 5.18 are shown the number of increased call acceptance performance versus the arriving lightpath requests on the US topology, USIP topology and NSFNET network topology respectively. In Figure 5.16 IAC performance varies from 1 to 4 against shortest path routing and 4 to 16 against alternate routing depending on the volume of arriving lightpath connection requests and availability of resource in the network. It shows that IWD based survivable routing consistently performs better than alternate and shortest routing in all scenarios. At low load, all three approaches accept almost similar quantity of lightpath requests. It is observed from Figure 5.17 that IWD-SR approach accepts more number of call connection requests as compared to the shortest routing and alternate routing approaches.

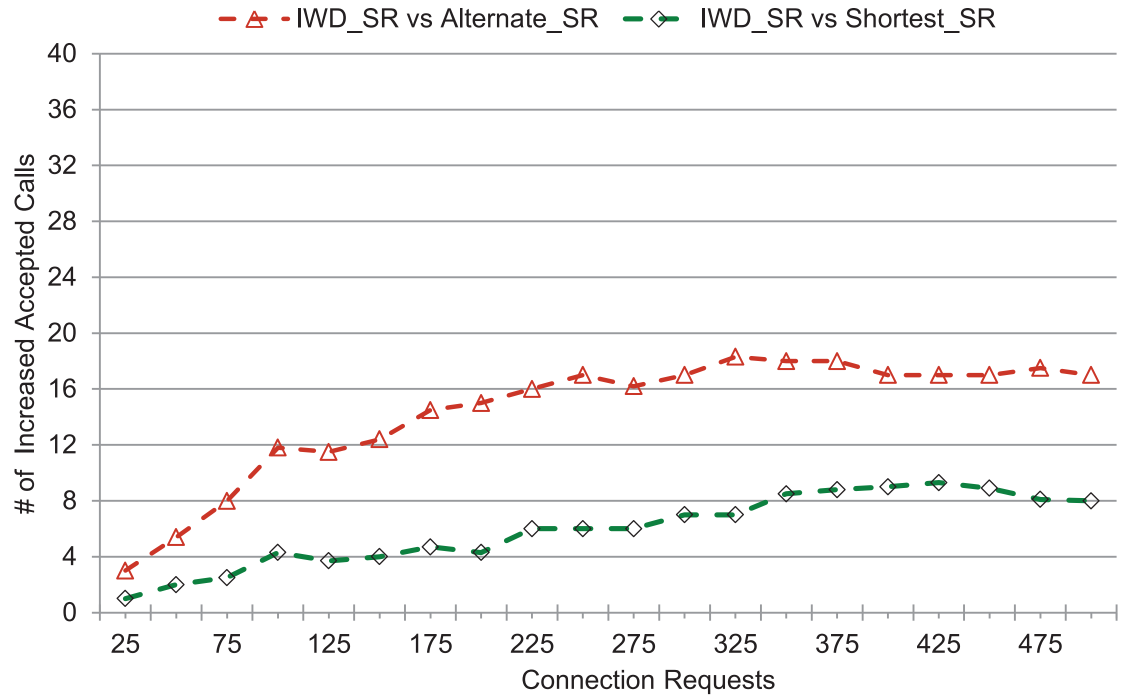


Figure 5.16: Increased Accepted Call Performance on US Network Topology

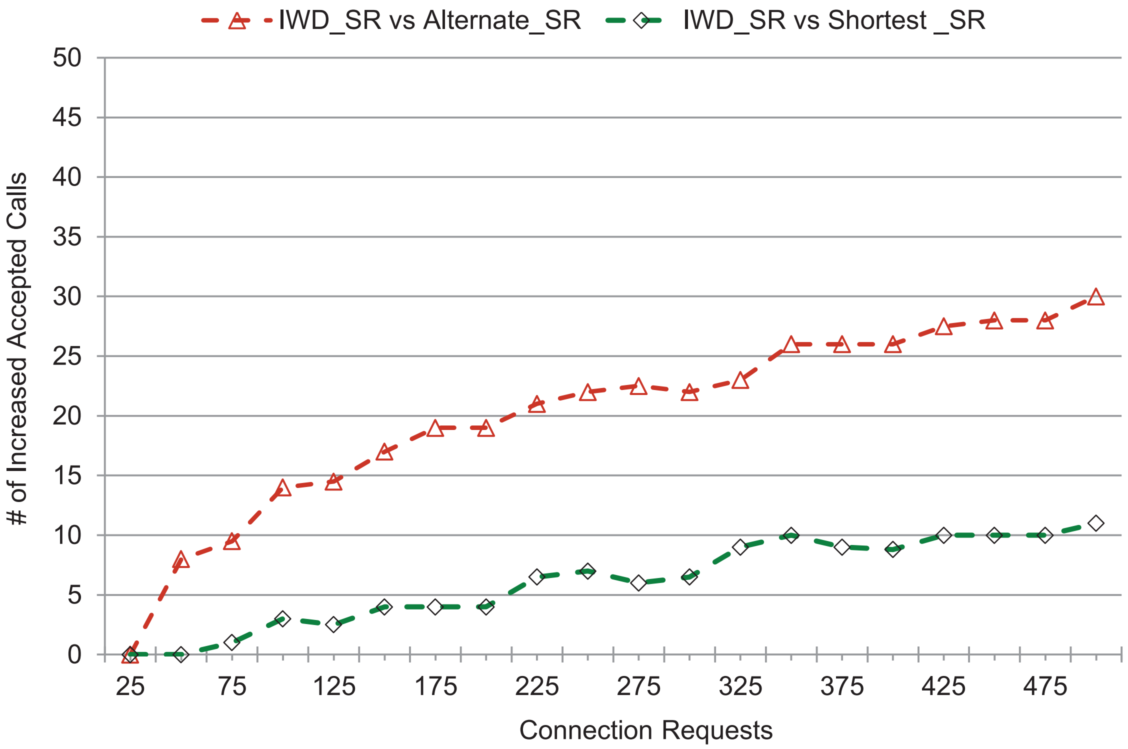


Figure 5.17: Increased Accepted Call Performance on USIP Network Topology

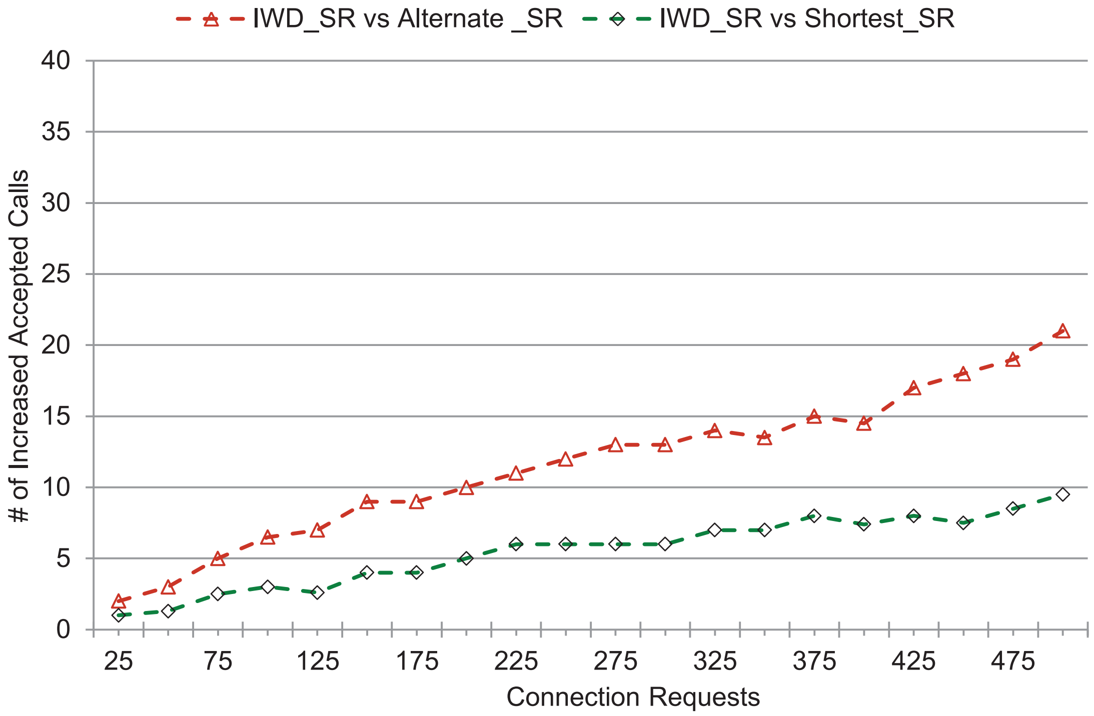


Figure 5.18: Increased Accepted Call Performance on NSFNET Network Topology

In Figure 5.18 value of IAC of IWD-SR varies from 1 to 10 and 2 to 20 with respect to shortest path routing and alternate routing approach respectively. In all of the scenarios, IWD based survivable routing accepts significantly more lightpath requests than other two routing approach. When arrival rate of lightpath traffic is less, IWD-SR shows insignificant improvement in the number of call accepted. This can be attributed to the fact that almost all lightpath request can be successfully satisfied by all three routing algorithms. Performance improvement shown in plots for IWD based survivable routing has minor variation at low lightpath requests. Overall observation from the results on different network topology implies that IWD based survivable routing approach can accommodate more lightpath requests in the network as compared to other two routing approach.

5.5.4 Performance Analysis of IWD Survivable Routing with ACO and BCO based Approach

In this section, for the observation of the significant of performance shown by the IWD-SR survivable lightpath routing strategy through swarms of water drops approach has been also compared with the ant based ACO algorithm and artificial bees based BCO optimization approach for survivable lightpath protection in wavelength routed WDM networks. Similar quantity of agents used in each approach.

For all the three test network topology, the number of available wavelength per link is considered to be 15. The parameters, attributes and values of various control parameters which have been used in our simulation are summarized in Table 5.2.

Table 5.2: Symbol and Simulation Parameters used for ACO and BCO

Symbol/Parameter	**Description**	**Value**
For Ant colony Algorithm		
α	Control parameter associated with deposited pheromone value	1
β	Control parameter associated with heuristic value	1
τ	Initial pheromone amount on each edge	4
ρ	Pheromone evaporation rate	0.1
η_{ij}	Heuristic desirability value	NA
τ_{ij}	Amount of pheromone on edge(i, j)	NA
$\Delta\tau_{ij}$	amount of pheromone deposited	NA
$H_{count}(ij)$	No of physical hops/nodes in the route (i, j)	NA
$P_{ij} = \dfrac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{j \notin V_{visited}} \tau_{ij}^{\alpha}\eta_{ij}^{\beta}}$	Probabilistic selection of an edge (i,j) for transition probability	NA
$\Delta\tau_{ij} = \dfrac{W_{free}}{W_{total}}$	Pheromone Deposited	
$\tau_{ij} = \tau_{ij} + \Delta\tau_{ij}$	Pheromone Update	NA
$\tau_{ij} = (1-\rho)\tau_{ij}$	Pheromone evaporation	
For Bee colony Algorithm		
P_{len}	Route length considered in terms of number of physical hops	NA
Υ	weightage of importance factor	0.5
$P_r^{sd} = \dfrac{e^{U_r^{sd}}}{\sum_{i=1}^{R_{sd}} e^{U_r^{sd}}}, \forall r \in R_{sd}$	Selection probability to choose route r from available routes R_{sd} for case of origin-destination pair (s, d)	NA
$U_r^{sd} = \Upsilon \dfrac{1}{P_{len}} + (1-\Upsilon)\dfrac{W_{free}}{W_{Total}}$	Bee's utilities function when choosing the route r between the (s, d) node pair	NA

Blocking Probability Performance

The blocking probability measurements for IWD based survivable routing in comparison to bee colony and ant colony based survivable routing approach is plotted in Figure 5.19, Figure 5.20 and Figure 5.21 over the US network topology, USIP network topology and NSFNET network topology respectively. It is inferred from the Figure 5.19 that the IWD-SR produces lowest blocking probability as compared to the other two compared there in. It is found that the blocking performance of all the approaches increases with the rise in the number of lightpath requests. However, in case of IWD it remains low throughout the range of observation. In particular, at lesser traffic load IWD performs significantly better than the other two approaches, but at higher traffic this reduces to a marginal improvement over the ACO and BCO counter parts. Similar behavior has been inferred from the results plotted in Figure 5.20 and Figure 5.21. In all the network topology, it has been observed from the plots that IWD based survivable lightpath routing approach is better than other two approach compared therein. It can be observed from the graphs that the blocking probability becomes almost flattened at higher lightpath requests due to the availability of less network resources.

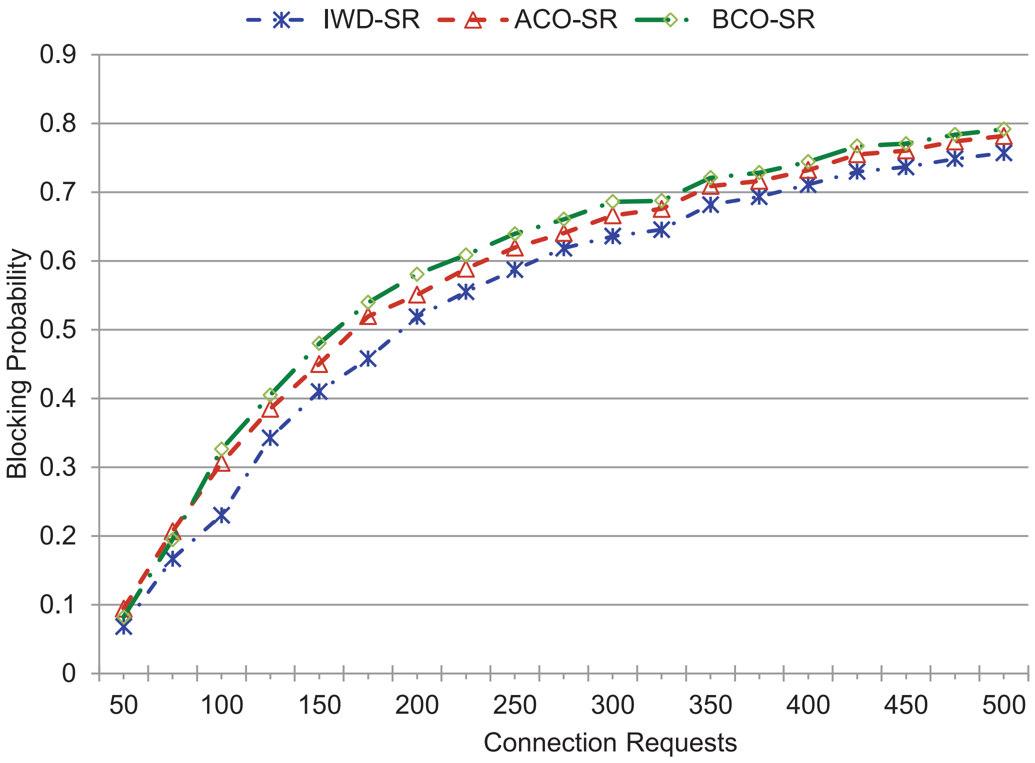


Figure 5.19: Blocking Performance on US Network Topology

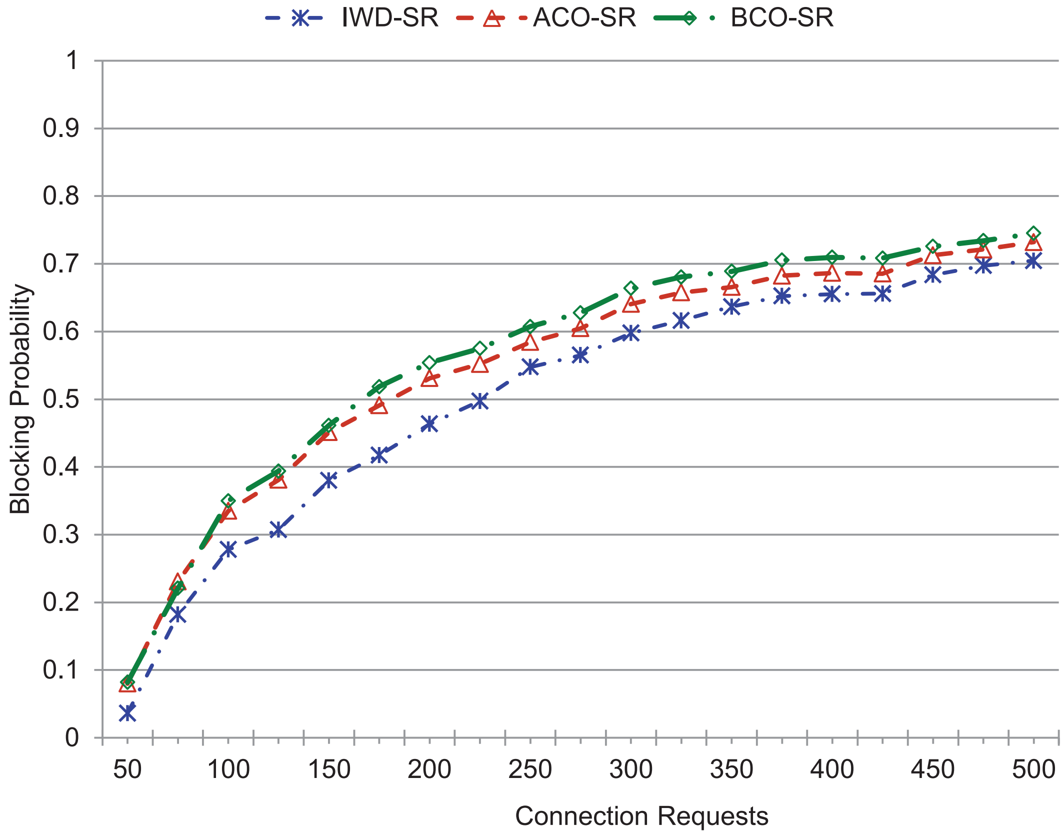


Figure 5.20: Blocking Performance on USIP Network Topology

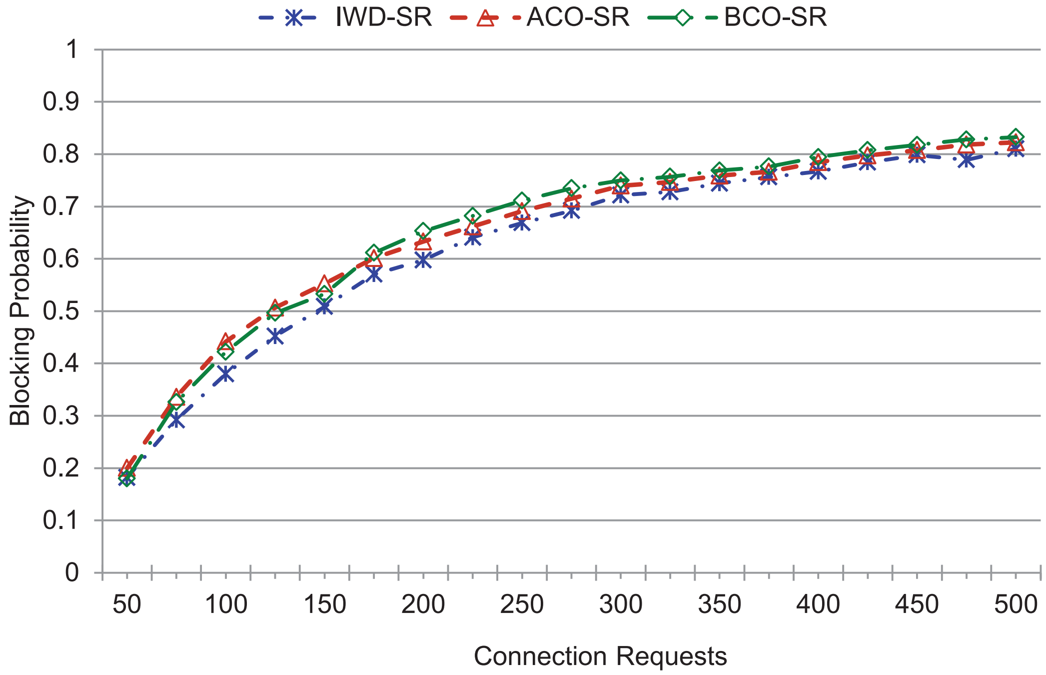


Figure 5.21: Blocking Performance on NSFNET Network Topology

These simulation studies carried over different network topologies under various traffic loads has demonstrated that IWD based routing algorithm has a better network performance and it achieve a better performance in terms of low blocking probability when used for dynamic survivable routing in WDM networks.

5.6 Summary

In this chapter, we have proposed an Intelligent Water Drops based survivable routing mechanism for dynamic wavelength-routed WDM networks with single link failure model. The survivable routing problem to determine primary and protection backup lightpath with backup path sharing based on IWD approach for dynamic traffic is considered. A heuristic algorithm inspired from the intelligence behavior of swarms of intelligent water drops, a framework is proposed to find the optimal link disjoint paths between a source-destination node pair to provide single link failure protection in WDM network. The effectiveness of proposed approach is shown through the results obtained by various extensive simulations. The proposed intelligent algorithm for the lightpath discovery mechanism, determines the link disjoint optimal paths from source to destination for each incoming connection request to provide protection against a single link failure. Our proposed algorithm satisfies the requirements of dynamic network adaptability and distributiveness by the intelligence of swarms of water drops. Simulation results on three different network topologies show that IWD based survivable routing approach has better call acceptance probability as compared to fixed alternate routing, shortest path routing, BCO and ACO based routing approach and achieves better network performance. The extensive simulation results demonstrate the ability and effectiveness of proposed IWD model for solving survivable routing problem in the optical WDM networks. Survivable protection routing through the IWD based approach is better in achieving the performance and is more adaptive compared to traditional routing approaches.

CHAPTER - 6

Conclusions and Future Directions

The Wavelength Division Multiplexing (WDM) technology plays a major role in the transport of high bandwidth data of Internet backbone infrastructure. High bandwidth requirements of Internet and intranet usage, multimedia applications can be accommodated by the incorporation of multiwavelength channels in WDM networks. Hence, the wavelength routed WDM network is a popular solution and resolves the bandwidth scarcity problems in the next generation Internet applications.These high capacity networks need a roboust protection and restoartion survivable mechanism to restore the operation within the specified criteria to ensure the quality of service and reliability of the network services. The survivable routing will provide reliable and efficient traffic aware mechanisms, which reduces the data loss during service interruptions in the backbone network. Service providers need to ensure efficient utilization of network resources for cost effective performance oriented services. In the present study, WDM survivable lightpath routing has been orchestrated carefully to achieve lower call blocking performance to improve the resource utilization of the networks. The thesis has contributed various survivable routing mechanisms in WDM optical networks and presenting findings of the work in summary in this chapter.

The analysis and findings of different chapters are summarized in the followings:

In Chapter 2, an adaptive hybrid protection mechanism has been proposed which provides lightpath survivability in the wavelength routed WDM networks. The proposed strategy is an integrated approach which utilizes the multitudinous strength and benefit of traditional protection and dynamic restoration approach to improve the capacity benefits, blocking probability and restoration efficiency in WDM networks. In our integrated hybrid mechanism at the time of honoring each of the arriving incoming connection requests, a primary working lightpath and a set of possible minimum proactive backup protection paths are identified to handle a failure situation. When a fault occurs, restoration bandwidths are allocated dynamically to one of these readily available pre provisioned backup paths to restore the disrupted lightpath traffic. Hence, it greatly reduces the overhead caused by discovering restoration routes dynamically after the failure, thus increasing the network resources by allowing backup paths to assign channel bandwidths at failures. Since multiple pre-provisioned routes are at the source node's routing table, mostly backup routes are readily available during the restoration process, thereby improving the setup and recovery process. Intelligently sufficient backup routes are pre-provisioned for each outgoing primary traffic, which may ensure more possibility of restoration of affected request on link failures. The simulation results obtained from the different representative network topologies reveal that the proposed integrated hybrid scheme provides a significant improvement in the performance of blocking probability, network resources and restoration efficiency when compared with the traditional restoration and protection schemes.

In the network the requirements of the users may not be of same nature and therefore, the network has to cater different type and levels of services.Thus, we have also proposed a heuristic scheme of hybrid nature of services and traffic and it’s analytical model for the multi-categorized traffic for distinct service level has been developed to handle multi-level of traffic in a survivable WDM optical network. The proposed strategy has been analyzed and simulated to evaluate the performance of multi-categorized hybrid traffic under different combination of traffic scenarios. The simulation study confirms the superiority of multi-categorized traffic in terms of blocking performance and claims improved resource utilization. The findings of the chapters may, thus, be useful to predict the network performance in case of single level of traffic as well as of multilevel service provisionings in a survivable WDM networks.

The selection and utilization of primary and backup paths is a concern for optimized performance of survivable routing and wavelength assignment in WDM optical network. Hence, for improved performance of wavelength routed network, the well designed SRWA scheme is critically important. In Chapter 3, we discussed three heuristic approaches of route selection, influenced from different combination of path pair length, for survivable RWA problem. For each incoming connection requests, these heuristic SPP, SLPP and LSPP schemes consider the different path length combinations in the primary route and backup route selections. These routing heuristic strategies for survivable WDM networks are studied to describe the influence of length of route on the network performance. Length of the primary and backup path pair influences the blocking performance and network resources in wavelength routed optical networks. It also affects the restoration switching delay involved in the recovery process of failures. Performance of these routing heuristics strategy are extensively simulated and analyzed on the three scenarios, i.e. changing the network topology, lightpath load and wavelengths availability per fiber link. Simulation results reveal that Shortest Path Pair survivable routing strategy outperform the Shortest Longest Path pair and Longest Shortest Path pair strategy while Shortest Longest Path pair strategy is better than Longest Shortest Path pair strategy.It has also been concluded that call acceptance performance of Shortest Path Pair survivable scheme is significantly better than other two. The proposed heuristics have further been compared with the existing joint path pair selection strategy. It has been observed that SPP heuristic performs significantly better with respect to joint path pair at low to moderate traffic , however, at high traffic relative improvement is not significant. Thus our proposed heuristics confirms that intelligently selecting routes can achieve superiority of network performance in wavelength routed WDM optical networks.

These heuristics mainly consider path length and do not accounting the network resource and energy parameters. The energy consumptions drastically increases due to various legion new services and increasd Internet users. It is expected to grow in near future rapidly. However, in WDM networks, the reduction of energy consumption either through technologies or by the mechanism and operation of the network management becomes an important strategy. Thus, the last subsection of third chapter focuses on resource and energy aware routing scheme by proposing a suitable algorithm and to analyze the network performance. The performance has been evaluated under the constraint of resource and energy metrics. The proposed algorithm shows superior blocking and energy performance with respect to other compared strategies therein.

In Chapter 4, a survivable lighpath routing and wavelength assignment strategy using maximum network flow concepts of network graph theory has been proposed. This approach determines a wavelength and route simultaneously for a incoming connection requests. Mostly, all routing and wavelength assignment algorithms attempted the route selection and channel assignments problem separately. In this approach, flow network represents the wavelength resources appropriately such that survivable routing and wavelength assignment problem in survivable WDM networks is solved efficiently. It gives all possible wavelength continuous flow paths that maximizes the number of lightpaths that can be established between a source-destination node pair of the requests.

Simulation results taken over three different network topologies confirm that the maximum network flow based lightpath routing for survivable network has significantly better call acceptance ratio when compared against conventional alternate fixed routing, shortest path and K-shortest routing approach.

In Chapter 5, A heuristic algorithm inspired from the intelligence behavior of swarms of intelligent water drops is discussed and a framework is proposed for lightpath protection in survivable WDM network with shared backup paths. IWD is a probabilistic technique used for solving complex survivable routing problem in dynamic wavelength-routed WDM optical networks with single link failure model. The purpose of our proposed algorithm is to maximize the number of established lightpaths of traffic and to minimize the network resource utilized in the establishment of connection requests using intelligent water drops. The effectiveness of proposed approach is shown through the results obtained by extensive simulation. The proposed algorithm satisfies the requirements of dynamic network adaptability by the intelligence of swarms of water drops. Simulation results on three network topologies reveal that Intelligent Water Drops based survivable routing mechanism has lower call blocking probability and achieves higher network throughput against traditional fixed alternate routing and shortest path routing approaches. Further the proposed algorithm has also been compared with the other nature inspired Ant Colony Optimization (ACO) and Bee Colony Optimization (BCO) based approach. The proposed algorithm is found to be a better choice in survivable routing decision. The extensive simulation results demonstrate the ability and effectiveness of proposed IWD model for solving survivable routing problem in the real world optical networks.

In summary the present thesis reports an integrated hybrid approach for network survivability in WDM network and claims an improvement in blocking probability and restoration performance as compared to the existing conventional preplanned protection and restoration approaches corresponding to single category of traffic. The problem has been extended for the multi-categorized traffic scenarios in a multiservice network by proposing a heuristic scheme for hybrid nature of services and traffic to handle multi-categorized level of traffic. The analysis confirms the superiority of multi-categorized traffic in terms of blocking performance and network resource utilization.

The thesis proposes three heuristics to evaluate the influence of the pair of primary and backup route on the network blocking performance and claims better performance at low to moderate traffic with respect to JPP strategy. The proposed route selection strategy also includes resource and energy network parameter in the analysis to show a superior blocking and energy consumption. Further, an unified approach for route and wavelength assignment has been attempted employing maximum flow concept of graph theory and findings have been compared with the conventional strategies of the literature to show an improvement in the blocking performance in case of our proposed strategy.Finally, the thesis explores the suitability of customized IWD based nature inspired optimization technique to solve the survivable routing problem in WDM network.

The research work carried out for the completion of this thesis assumes communication links as single fiber links. Thus, as an extension to this work the single fiber link constraint can be relaxed and the work can be extended for multiple fibers. In the current work, proposed survivable routing mechanisms are designed to handle only single link failure situations, thus multi-link failure scenario can be taken as a further extension to this work.

In the current work, network nodes are assumed as non-wavelength convertiable nodes. The wavelength converters are used to relax the wavelength continuty constraint in WDM networks but the use of multple converters in the lightpath degrade the network performance and network cost increases. Therefore, number of convertors in the network needs to be minimized. Moreover, these convertor nodes are required to be placed at some critical locations in the network to enhance the performance. Hence, wavelength converter placement problem in the WDM network can also be taken as an extension to this work.

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List of Publications

1. Dinesh Kumar Tyagi, V.K. Chaubey, "Survivable Routing with Path Length Constraint in WDM Networks", International Journal of Applied Engineering Research, Volume 11, Number 1 (2016) pp 404-410.
2. Dinesh Kumar Tyagi, V.K. Chaubey, "Routing and Wavelength Assignment in WDM Network using IWD based Algorithm", International Conference on Computing Communication and Automation (ICCCA-2016), 29-30th, April, 2016.
3. Dinesh Kumar Tyagi, V.K. Chaubey, "Performance Evaluation of Path Length based Routing Strategies for Survivable WDM Network" Second International Conference on Information and Communication Technology for Competitive Strategies (ICTCS-2016),Udaipur, Rajasthan, 2016.
4. Dinesh Kumar Tyagi, Virendra S Shekhawat, V.K. Chaubey, "Resource Efficient Survivability Approach for Resilient WDM Optical Networks", Proceedings of the International Conference on Advances in Computing, Communications and Informatics (ICACCI-2012), Chennai, India, ACM, pp. 619-624, Aug 2012.
5. Dinesh Kumar Tyagi , V. K. Chaubey,"Maximum Network Flow Aware Multi-Lightpath Survivable Routing in WDM Networks", Proceedings of Third International Conference on ICTCS 2017. 10.1007/978-981-13-0586-3_72.
6. Dinesh Kumar Tyagi, V.K. Chaubey,"Dynamic Lightpath Protection through Intelligent Water Drops based Algorithm in Optical Networks, " IEEE- International Conference on Computing, Power and Communication Technologies (GUCON), Greater Noida ,India, pp.1130-1135,2018.
7. Dinesh Kumar Tyagi, V.K. Chaubey, "IWD-SLR Intelligent Water Drops based Survivable Lightpath Routing in WDM optical networks", IEEE Access Journal of IEEE .(under revision)
8. Dinesh Kumar Tyagi, V.K. Chaubey,"Resource and Energy Aware Survivable Shared Protection in Wavelength Routed Optical Networks", Optical Fiber Technology. (Communicated)

9. Dinesh Kumar Tyagi, V.K. Chaubey, “Resource Aware Multi Lightpath Routing in WDM Optical Networks”, Elsevier, International Journal for Light and Electron Optics. (Communicated)
10. Dinesh Kumar Tyagi, V.K. Chaubey, “Adaptive Hybrid Survivability Approach for Multi-Categorized Traffic in Multiservice WDM Networks”, International Journal of Communication Systems, Wiley. (Communicated)

Brief biography of Candidate

Dinesh Kumar Tyagi was a research scholar under faculty development program in the Department of Computer Science & Information Systems at Birla Institute of Technology & Science (BITS- Pilani), Pilani Campus , since July 2004. He is currently working as Assistant Professor in Department of Computer Science and Engineering, Malaviya National Institute of Technology (MNIT) Jaipur, since July 2013 and since then working as a part time Ph. D. student of BITS-Pilani. He obtained his B.E. degree in Computer Science & Engineering from Madan Mohan Malaviya Engineering College, Gorakhpur and M.Tech. (Computer Science & Engineering) from Motilal Nehru National Institute of Technology (MNNIT), Allahabad in 2001 & 2003 respectively. His research interests are Optical WDM Networks, RWA algorithms in Wavelength Routed Optical Networks.

Brief biography of Supervisor

Prof. V. K. Chaubey is a Professor and HOD in Electrical and Electronics Engineering Department at Birla Institute of Technology and Science (BITS-Pilani), Pilani Campus. He obtained his M.Sc. with specialization in Electronics and Radio Physics and Ph.D. in Fiber Optics Communication from Banaras Hindu University (BHU), Varanasi in 1985 and 1992 respectively. He is a senior member of IEEE (USA) and Fellow, IETE (India). He has nearly 100 publications in International, National Journals and Conference proceedings. His research interests are Optical waveguide and Integrated Optics, Wireless and Optical Communication Networks. He has guided/guiding several Ph.D. students in the related area.