Routing and Wavelength Assignment Algorithms for WDM Networks

A

Thesis

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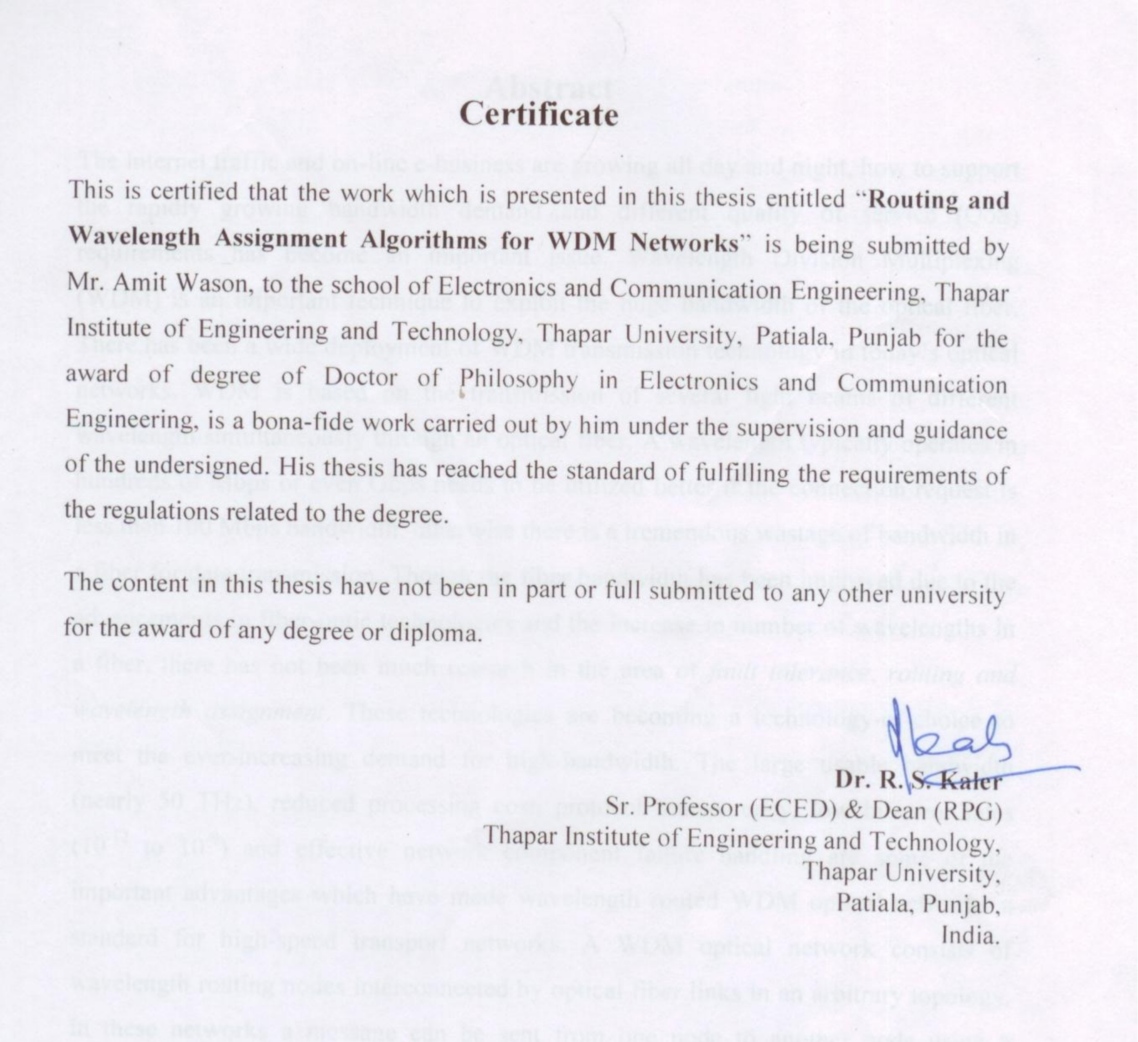

Certificate

This is certified that the work which is presented in this thesis entitled "**Routing and Wavelength Assignment Algorithms for WDM Networks**" is being submitted by Mr. Amit Wason, to the school of Electronics and Communication Engineering, Thapar Institute of Engineering and Technology, Thapar University, Patiala, Punjab for the award of degree of Doctor of Philosophy in Electronics and Communication Engineering, is a bona-fide work carried out by him under the supervision and guidance of the undersigned. His thesis has reached the standard of fulfilling the requirements of the regulations related to the degree.

The content in this thesis have not been in part or full submitted to any other university for the award of any degree or diploma.

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Abstract

The Internet traffic and on-line e-business are growing all day and night, how to support the rapidly growing bandwidth demand and different Quality of Service (QoS) requirements has become an important issue. Wavelength Division Multiplexing (WDM) is an important technique to exploit the huge bandwidth of the optical fiber. There has been a wide deployment of WDM transmission technology in today's optical networks. WDM is based on the transmission of several light beams of different wavelength simultaneously through an optical fiber. A wavelength typically operates in hundreds of Mbps or even Gbps needs to be utilized better if the connection request is less than 100 Mbps bandwidth, otherwise there is a tremendous wastage of bandwidth in a fiber for data transmission. Though the fiber bandwidth has been improved due to the advancements in fiber-optic technologies and the increase in number of wavelengths in a fiber, there has not been much research in the area of *fault tolerance, routing and wavelength assignment*. These technologies are becoming a technology-of-choice to meet the ever-increasing demand for high-bandwidth. The large usable bandwidth (nearly 50 THz), reduced processing cost, protocol transparency, low bit-error rates (10^{-12} to 10^{-9}) and effective network component failure handling are some of the important advantages which have made wavelength routed WDM optical networks a standard for high-speed transport networks. A WDM optical network consists of wavelength routing nodes interconnected by optical fiber links in an arbitrary topology. In these networks a message can be sent from one node to another node using a wavelength continuous path called a *lightpath* and is uniquely identified by a physical route and a wavelength. It is required that the same wavelength should be used on all the links along the selected route and this constraint is known as the *wavelength continuity constraint*. Typically the traffic demand in these networks can be static, dynamic or scheduled. In *Static Lightpath Establishment* (SLE), the goal is to establish lightpaths so as to optimize certain objective function (minimizing wavelength usage, congestion, blocking and maximizing single-hop traffic, etc.). The *Dynamic Lightpath Establishment* (DLE) problem is concerned with the establishment of lightpaths with an objective of increasing the average call acceptance ratio when connection requests arrive and depart from the network dynamically. Hence, the objective is to route the demands

to maximize the reuse of network resources. Like any communication network WDM networks are prone to hardware failure (such as routers and/or switches and cable cuts) and software (protocol) bugs. WDM networks carry a huge volume of traffic maintaining a high level of service availability. It is essential to incorporate fault-tolerance into QoS requirements. The deployment of WDM network is increasing in today's public Internet. Reliability and consistency are the important factors which must be taken into consideration before the deployment of any system. The fault tolerance could be provided at the optical layer or at the higher client (electrical) layers, each of which has its own merits. The optical layer has faster fault tolerance time and the use of wavelength channels in an optical layer is very optimal. Routing problem, Wavelength Assignment (WA) problem, Routing and Wavelength Assignment (RWA), Fault tolerance and survivability are some of the important problems which can increase the efficiency of WDM networks and are thus receiving a lot of attention recently.

Keeping in view these aspects, the objectives of research were formulated which are listed as below:

1. To study and analyse the existing wavelength assignment algorithms and to develop new algorithm of wavelength assignment for better performance in wavelength division multiplexed networks.
2. To study and analyse the existing routing algorithms and to develop new effective routing algorithms for survivable wavelength division multiplexed networks.
3. To compare the newly developed routing and wavelength assignment algorithms with the existing algorithms in terms of blocking for wavelength division multiplexed network.

To provide methods for effectively addressing the RWA problem, a novel framework has been developed that relies on mathematical models for routing in static and dynamic scenarios. In this thesis, probabilistic mathematical models are proposed and investigated for achieving better blocking performance of such networks. It has been demonstrated that these proposed mathematical models are capable of achieving better performance than the earlier models. To arrive at this result, we have defined various metrics for measuring the efficiency of routing algorithms for both the static and dynamic demands. Using these metrics, a variety of simulations have been performed. It has been shown in the thesis that the use of proposed mathematical models is the key to achieve superior performance in all-optical networks. Wavelength assignment algorithms and routing schemes for restoration have also been proposed for the better performance of the optical WDM networks. Further, routing and wavelength assignment problem has been dealt as a single problem and solutions for this problem have been proposed and compared with the conventional solutions.

We have proposed the low complexity probabilistic mathematical models for the calculation and reduction of blocking probability in wavelength convertible as well as in wavelength non-convertible WDM optical networks. We have proposed four mathematical models; two of these models have been proposed for wavelength non–convertible WDM Networks, one model for wavelength convertible WDM networks and one of the models has been proposed which can be implemented on both wavelength convertible and non–convertible WDM Networks. These probabilistic mathematical models proposed have closed-form expression and do not require any simulated statistics. These models possess low implementation complexity and the computation used is quite efficient. These models suggest the choice of best optimum path and appropriate number of free wavelengths in the network. These models were then used to evaluate and improve the blocking performance and fairness of network topology such as NSFnet. The results showed that the models work well for larger networks having higher number of wavelengths and even for those networks which have larger load per link. These models can also be implemented easily on any network. Further, the blocking probability can be reduced to a large extent using these models. Also, it has been shown that the computation efficiency of the proposed models is very high.

Two effective algorithms named Most Used Wavelength Conversion (MUWC) and First Fit Wavelength Conversion (FFWC) have also been proposed and the performance of new wavelength assignment algorithms has been evaluated in terms of blocking probability. The results of proposed algorithms were compared with conventional wavelength assignment algorithms such as first-fit, best-fit, random and most-used wavelength assignment algorithms. These proposed approaches were found very effective for minimization of blocking probability of the optical WDM networks. The response of blocking probability of existing wavelength assignment algorithms with network having 10 nodes for varying load have also been analysed. Two new wavelength assignment strategies which used sparse wavelength conversion have been proposed which proved to be very effective as compared to the earlier algorithms in situations where there is no possibility of changing the mathematical model.

Further, two wavelength routing schemes have been proposed for survivable networks. These schemes have been proposed for dynamic provisioning of lightpath which proved to be very efficient in calculation and minimization of blocking probability and produced very effective results. To improve performance of all optical survivable WDM networks, techniques based on wavelength rerouting have been applied. Two rerouting algorithms named Shortest Path Wavelength Rerouting (SPWRR) algorithm and Lightpath Rerouting Algorithm (LRRA) for dynamic traffic in WDM optical networks have been proposed. These wavelength rerouting algorithm have also been employed on realistic WDM optical network topology (NSFnet) to investigate blocking performance and resource utilization. The key advantage of these algorithms as compared to conventional routing and wavelength assignment algorithms is that these are very simple in nature and require less service disruption time. The results have also proved that LRRA can be implemented to huge networks for good blocking performance of the network.

Also, grooming and RWA problems have been dealt as a single problem and different solutions have been provided for this problem. These solutions have been used to evaluate the blocking performance of realistic networks such as NSFnet and EUPAN Networks. Hence these solutions can be used to improve the performance of a network on the basis of blocking probability. Further, a problem of enhancing multiple-fault tolerance in the path protected wavelength–routed all optical WDM networks has been discussed. Different mechanisms have been proposed for fault tolerance which were used to combat multiple link failures such as, Fault Tolerant Routing and Wavelength Assignment (FTRWA) algorithm and Survivable Routing and Wavelength Assignment Algorithm (SRWA). The comparison of these algorithms has been made with algorithms mentioned in literature. These algorithms have been implemented on different optical networks with multiple faults and proved to be effective for variable load on the nodes. These algorithms worked well with the changing load. Two generic routing and wavelength assignment algorithms (GRWA-I & GRWA-II) have been proposed for optimization and minimization of blocking probability. Using these routing and wavelength assignment algorithm the blocking probability can be reduced to a large extent. The proposed algorithms have also been compared with conventional routing and wavelength assignment algorithms.

The investigations thus carried out in this thesis results in blocking free environment in an optical network. The mathematical models and the algorithms proposed in the thesis are very simple in operation and do not require any simulation statistics. Some of the solutions suggested in this thesis can be used for fault tolerance in survivable wavelength Division multiplexed optical network.

The results reported in this thesis have been published in the form of thirteen papers in refereed international journals as per list enclosed.

List of publications

The work reported in this thesis has resulted in the following publications:

1. Amit Wason, R. S. Kaler, “Blocking performance analysis of wavelength assignment algorithms in WDM networks,” *International Journal of Microwave and Optical Technology*, vol. 3, no. 1, pp. 54-61, January 2008.

2. Amit Wason, R. S. Kaler, “Rerouting technique with dynamic traffic in WDM optical networks,” *Optical Fiber Technology -Elsevier Science*, vol. 16, no. 1, pp. 50-54, January 2010.

3. Amit Wason, R. S. Kaler, “Lightpath rerouting algorithm to enhance blocking performance in all-optical WDM network without wavelength conversion,” *Optical Fiber Technology -Elsevier Science*, vol. 16, no. 3, pp. 146-150, June 2010.

4. Amit Wason, R.S. Kaler, “Blocking in wavelength-routed all-optical WDM networks,” *Optik–International Journal for Light and Electron Optics-Elsevier Science*, vol. 121, no. 10, pp. 903-907, June 2010.

5. Amit Wason, R. S. Kaler, “Routing and wavelength assignment in wavelength-routed all-optical WDM networks,” *Optik -International Journal for Light and Electron Optics -Elsevier Science*, vol. 121, no. 16, pp. 1478-1486, September 2010.

6. Amit Wason, R. S. Kaler, “Blocking in wavelength–routed all-optical WDM network with or without wavelength conversion,” *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 121, no. 23, pp. 2162-2165, December 2010.

7. Amit Wason, R. S. Kaler, “Fault-Tolerant Routing and Wavelength assignment algorithm for multiple link failures in Wavelength–Routed all-Optical WDM Networks,” *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 2, pp. 110-113, January 2011.

8. Amit Wason, R. S. Kaler, "Blocking in wavelength–routed all-optical WDM network with wavelength conversion," *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 7, pp. 631-634, April 2011.

9. Amit Wason, R. S. Kaler, "Wavelength Assignment Algorithms for WDM optical networks," *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 10, pp. 877-880, May 2011.

10. Amit Wason, R. S. Kaler, "Generic Routing and Wavelength Assignment Algorithm for a Wavelength-Routed WDM network," *Optik –International Journal for Light and Electron Optics-Elsevier Science*, vol 122, no. 12, pp. 1100-1106, June 2011.

11. Amit Wason, R. S. Kaler, "Survivable Routing and Wavelength assignment algorithm for multiple link failures in Wavelength–Routed all-Optical WDM Networks," *Optik –International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 12, pp. 1095-1099, June 2011.

12. Amit Wason, R. S. Kaler, "Genetic-II Routing and Wavelength Assignment Algorithm for a Wavelength-Routed WDM network," *Optik –International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 12, pp. 1107-1112, June 2011.

13. Amit Wason, R. S. Kaler, "Blocking Probability Calculation in Wavelength–Routed All–Optical Networks," *Optik -International Journal for Light and Electron Optics-Elsevier Science* In Press, Corrected Proof, Available online 21 January 2011.

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(Amit Wason)

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List of Acronyms

ANSI	:	American National Standard Institute
AON	:	All-Optical Network
ATM	:	Asynchronous Transfer Mode
AWG	:	Arrayed Waveguide Gratings
BE	:	Branch-and-Exchange
CWDM	:	Coarse Wavelength Division Multiplexing
DARPA	:	Defense Advanced Research Projects Agency
DFB	:	Distributed Feedback
DLE	:	Dynamic Lightpath Establishment
DoD	:	Department of Defense
D-PWS	:	Dynamic Preferred Wavelength Sets
DWDM	:	Dense Wavelength Division Multiplexing
DWR	:	Dynamic Wavelength Routing
EDFA	:	Erbium Doped Fiber Amplifier
ETSI	:	European Telecommunications Standard Institute
EUPAN	:	European Network
FDDI	:	Fiber Distributed Data Interface
FDM	:	Frequency Division Multiplexing

FFWC : First Fit Wavelength Conversion

FPLC : Fixed Path Least Congestion

FR : Fixed Routing

FTRA : Fault Tolerant Routing Algorithm

FTRWA : Fault Tolerant Routing and Wavelength Assignment

FTWA : Fault Tolerant Wavelength Assignment

FWC : Fixed Wavelength Conversion

GMPLS : Generalized Multiprotocol Label Switching

HOS : Hybrid Optical Switch

IETF : Internet Engineering Task Force

IFARWA : Improved Fixed-Alternate Routing and Wavelength Assignment.

ILP : Integer Linear Programming

IP : Internet Protocol

ITU-T : International Telecommunication Union-Telecommunication Standardization sector

LAN : Local Area Network

LED : Light Emitting Diode

LLN : Linear Lightwave Network

LLR : Least Loaded Routed

LRRA : Lightpath Re-Routing Algorithm

LW : Length Weighted

MAC	:	Medium Access Control
MAN	:	Metropolitan Area Network
MPLS	:	Multiprotocol Label Switching
MRWA	:	Multicast Routing and Wavelength Assignment
MSPP	:	Mixed Shared Path Protection
MTV-WR	:	Move-To-Vacant Wavelength Retuning
MUWC	:	Most Used Wavelength Conversion
NFS	:	Network File System
NP	:	Nondeterministic Polynomial
NSFNET	:	National Science Foundation Network
OBS	:	Optical Burst Switching
OCS	:	Optical Circuit Switching
OEO	:	Optical-Electronic-Optical
OVPN	:	Optical Virtual Private Networks
OXC	:	Optical Cross Connect
PWRP	:	Pre-emptive Wavelength Reservation Protocol
QoS	:	Quality of Service
RFC	:	Request for Comments
RLD	:	Random Lightpath Demand
RRAC	:	Re-Routing at Connection

RRAL	:	Re-Routing at Lightpath
RWA	:	Routing and Wavelength Assignment
SDH	:	Synchronous Digital Hierarchy
SLD	:	Scheduled Lightpath Demand
SLE	:	Static Lightpath Establishment
SOA	:	Semiconductor Optical Amplifier
SONET	:	Synchronous Optical Network
SPWRR	:	Shortest Path Wavelength Re-Routing
SRWA	:	Survivable Routing and Wavelength Assignment
TCP	:	Transmission Control Protocol
TDM	:	Time Division Multiplexing
UDP	:	Universal Datagram Protocol
VC	:	Virtual Channel
VP	:	Virtual Path
WA	:	Wavelength Assignment
WADM	:	Wavelength Add-Drop Multiplexer
WAN	:	Wide Area Network
WDM	:	Wavelength Division Multiplexing
WI	:	Wavelength Interchange
WIXC	:	Wavelength Interchange Cross-connect

WRMSP : Wavelength Reusing Migrating Sharing Protocol

WS : Wavelength Selective

WSXC : Wavelength Selective Cross-connect

WW : Wavelength Weighted

WXC : Wavelength Selective cross-connect or Wavelength Routing Switch

List of Symbols

P_B^r	Blocking probability of r routes
P_{BW}^r	Blocking probability caused by insufficient wavelength
P_{BC}^r	Blocking probability caused by lack of converter
L^r	Load of the route r
P_B	Overall blocking probability of the network
P_{Bavg}	Average Blocking Probability
B_{sd}	Blocking probability of a source destination (s-d) pair
B_{sd}^r	Blocking probability of r routes for a s-d pair
G_p	Weighted Bidirectional Graph
L_{sd}^r	Load of the route r for a s-d pair
C	Total Number of Converters (*for Model-I, II, III*)
Ch	Number of Channels
l	Route length of path selected
N	Number of nodes in WDM network
$N\lambda$	Number of free wavelengths
r	Number of routes available
R	Set of all Routes

V	Set of all Network Nodes
W	Total Number of Wavelengths
$B(C, L_{sd}^{r})$	Erlang loss formula for L_{sd}^{r} load and C channels

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CHAPTER I

INTRODUCTION

The rapid growth of Internet traffic has been the driving force for faster and more reliable data communication networks. Networking is a very promising technology to meet these ever increasing demands. The influence of networking on an organization of the computer systems has been tremendous, especially in the last 30 years. The old model of a single computer catering computation needs of an organization has been replaced by single network in which a number of separate but interconnected computers carry out the job. Broadly speaking a computer network is an interconnected collection of interdependent computers that aid communication in numerous ways. Apart from providing a good communication medium, cost effectiveness and sharing of available resources (programs and data) are some of the advantages of networking. Nowadays, the need for error-free, high bandwidth communication channels has been on the rise. The services provided by computer networks are mainly remote information access. This rapid growth of internet traffic has been the driving force for faster and more reliable computer and data communication networks. Wavelength division multiplexing (WDM) is a very promising technology to meet the ever increasing demands of high capacity and bandwidth. In a WDM network several optical signals are sent on the same fiber using different wavelength channels. Sometimes, the term dense wavelength division multiplexing (DWDM) is used to distinguish the technology from the broadband WDM systems where two widely separated signals (typically 1310nm and 1550nm) share a common fiber. In DWDM up to 40 or 80 signals are combined on the same fiber. WDM networks are a viable solution for emerging applications, such as supercomputer visualization and medical imaging, which need to provide high data transmission rate, low error rate and minimal propagation delay to a large number of users [1].

Traditionally, only a small fraction of the fiber capacity was used, but by using WDM it is possible to exploit this huge capacity more efficiently [2]. The possibility to use the existing fibers more efficiently makes WDM a very attractive alternative commercially, as it is very expensive to install new fibers in the ground. This is the case especially in densely populated areas like cities, where fibers must be dug under streets etc. WDM technology has been recognized as one of the key components of the future networks. The commercialization of WDM technology is progressing rapidly. Most important for the development of the WDM technology was the invention of Erbium Doped Fiber Amplifier, (EDFA) an optical fiber amplifier in 1987. The optical fiber amplifier is a component capable of amplifying several optical signals at the same time without converting them first to electrical domain (opto-electronic amplification). It is also important to note that EDFAs can be used to amplify signals of different bit rates and modulations. Other important WDM components include lasers, receivers, wavelength division multiplexers, wavelength converters, optical splitters and tunable filters amongst others. There is also wide interest towards the optical networking in academic community as it offers a rich research field for scientists from the component level up to the network protocols.

1.1. Wavelength Division Multiplexing

Theoretically, fiber has extremely high bandwidth (about 25 THz [terahertz]) in the 1.55 low-attenuation band and this is thousands times of the total bandwidth of radio on the planet Earth [3]. However, only speed of a few gigabits per second is achieved because the rate at which an end user (a workstation) can access a network is limited by electronic speed, which is a few gigabits per second. Hence, it is extremely difficult to exploit all the bandwidth of a single fiber using a single high-capacity wavelength channel due to optical-electronic bandwidth mismatch or “electronic bottleneck.” The recent breakthroughs (Tb/s) are the result of two major developments: WDM, which is a method of sending many light beams of different wavelengths simultaneously down the core of an optical fiber and the EDFA, which amplifies signal at different wavelengths simultaneously regardless of their modulation scheme or speed.

WDM is essentially same as frequency division multiplexing (FDM), which has been used in radio systems for more than a century. For some reasons, the term FDM is used in radio communication but WDM is used in the context of optical communication, perhaps because FDM was studied by communication engineers and WDM by physicists [4]. The idea is to modulate optical signals at different wavelengths and to transmit the data simultaneously by combining resulting signals over the same optical fiber. A typical WDM link can be easily explained with figure (1.1). WDM systems use a carrier wave which is higher than that of an FDM channel by a million times in frequency (THz versus MHz). Within each WDM channel, it is possible to have FDM where the channel bandwidth is subdivided into many radio frequency channels each at a different frequency. This is called *subcarrier multiplexing*. A wavelength can also be shared among many nodes in a network by electronic *time division multiplexing*. Note that WDM eliminates the electronic bottleneck by dividing the optical transmission spectrum (1.55-micron band) into a number of non-overlapping wavelength channels. These channels coexist on a single fiber with each wavelength supporting a single communication channel operating at a peak electronic speed. The attraction of WDM is that a huge increase in available bandwidth can be obtained without the huge investment necessary to deploy additional optical fiber. The DWDM technique effectively increases the total number of channels in a fiber by using very narrow spaced channels [5]. Typically channel spacing ranges from 0.4 nm to 4 nm. Traditionally, a small fraction of the fiber capacity has been in use, but by using WDM it is possible to exploit this huge capacity more efficiently. In fact, the capacity of WDM link can be as large as terabits per second in a single fiber. Furthermore, the possibility of using the existing fibers more efficiently makes WDM commercially a very attractive alternative, as it is often very expensive to install new fibers in the ground. WDM technology has been recognized as one of the key components for the future networks and commercialization of WDM technology is progressing rapidly.

1.2. WDM Optical Network

A local WDM optical network may be constructed by connecting network nodes via two-way fibers to a passive star [6], as shown in figure (1.2). A node transmits data to the star on available wavelength using laser, which produces an optical information stream. The information stream from multiple sources is optically combined by the star and the signal power of each stream is split and forwarded to all nodes through their fibers. Communication between source and destination may either be single-hop or it may be multi-hop.

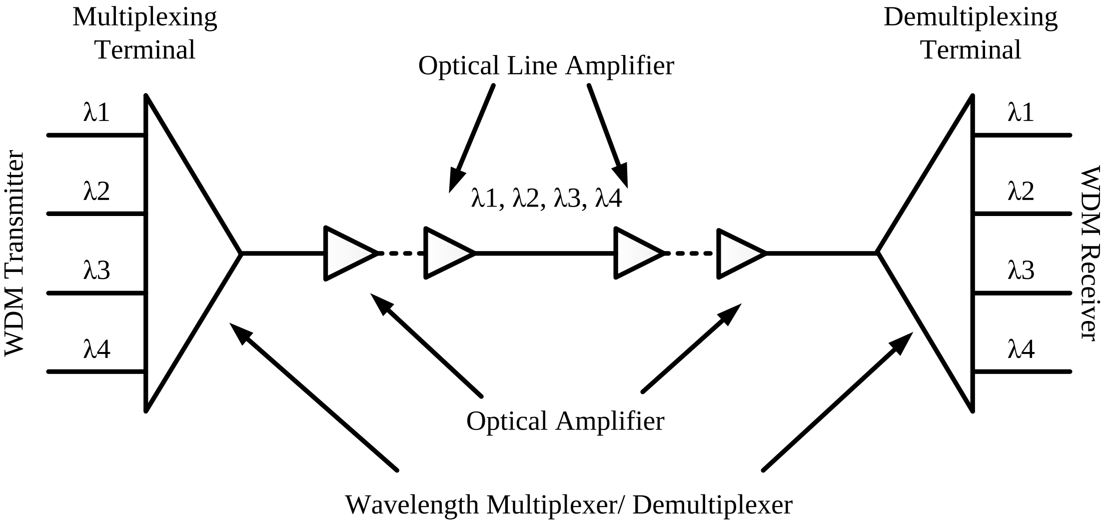


Figure 1.1: A Typical WDM point-to-point link

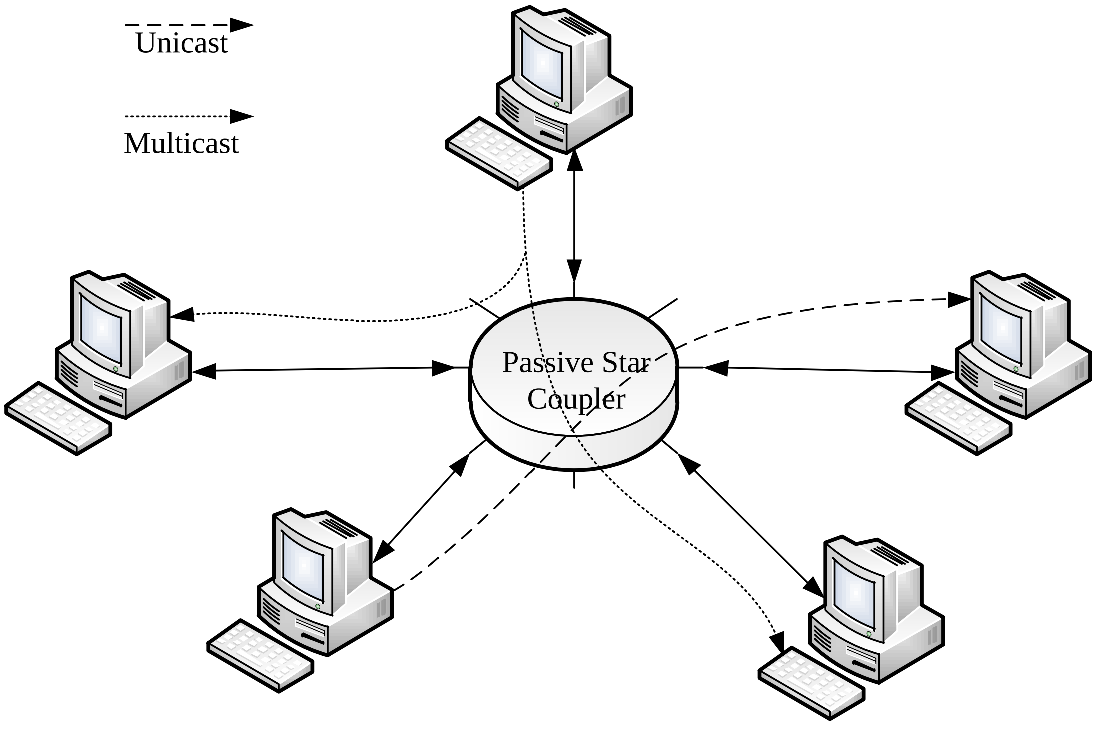


Figure 1.2: A passive-star based local optical WDM network

1.3. Wavelength Channels in Optical Spectrum

WDM systems can be classified further on the basis of the Wavelength channels used. The first WDM systems were so-called broadband WDM systems, using two widely-separated signals (typically at 1310 nm and 1550 nm). On the other hand, the term

DWDM refers to a technology used in backbone networks, where up to 40 or 80 signals are combined on the same fiber [7]. Furthermore, there is coarse wavelength division multiplexing (CWDM), where the channel spacing is 20nm in the range of 1270nm to 1610nm giving up to 18 channels in total. Unlike the other two, CWDM is targeted at metropolitan area networks. The International Telecommunication Union (ITU) has standardized the use of wavelength channels. Standard G.692 defines channel spacing for DWDM systems as 50 GHz or 100 GHz around the reference frequency of 193.10 THz, as depicted in figure (1.3). The reference frequency 193.10 THz corresponds to about 1550 nm, and hence the proposal is meant for the 1540 nm - 1560 nm pass band of the optical fiber.

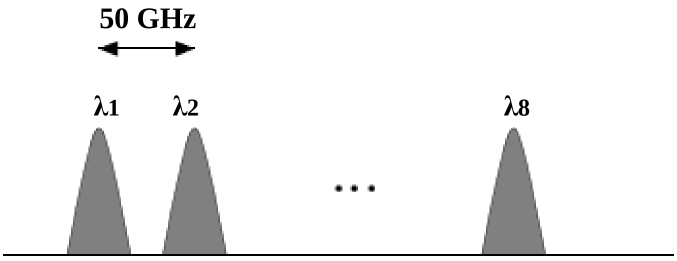


Figure 1.3: The optical spectrum and 8 wavelength channels.

1.4. All-Optical Networks

Initially, the WDM technique was used to increase the capacity of point-to-point optical links. At the end of each link the signal was converted back to the electrical domain and the gain was simply a larger link capacity. However, the trend has been towards transparent all-optical networks, where signal is routed through a network in optical domain. Something that was especially important for development of all-optical WDM networks was the invention of EDFA in 1987. The optical fiber amplifier, EDFA is a component capable of amplifying several optical signals at the same time without converting them first to the electrical domain (opto-electronic amplification). It is also worth noting that EDFAs can be used to amplify signals of different bit rates and modulations. Other important WDM components include light sources, tunable filters, optical switches, wavelength converters, optical amplifiers and wavelength division multiplexers. In future, these components will together enable us to build the transparent all-optical networks to meet the ever increasing capacity demands.

1.5. Components of All-Optical WDM Network

During recent years lots of efforts have been made for the development of better optical components to enable all-optical WDM-networks [8]. The most important components are light sources, tunable optical filters, optical switches and of course the fiber. Different components are briefly presented in the following sections.

1.5.1. Light Sources

One of the important elements of an optical system is the light source. For communication purpose, a good light source should be quickly tunable with a wide range of wavelengths. To make a component commercially attractive low price and low power consumption are vital parameters [9]. The time scale of tuning depends upon the technique used i.e. with optical packet switching the requirements are somewhere between microseconds and nanoseconds while with circuit switched WDM-networks the time scale is slower. Here is a list of several candidates for light sources [8, 10]:

1. Mechanically tuned lasers
2. Acousto-optically and electro-optically tuned lasers
3. Injection current tuned lasers
4. Switched sources
5. Array sources (using arrayed waveguide gratings (AWG) or distributed feedback (DFB) lasers)

Mechanically tuned lasers have a tuning time of the order of milliseconds and are thus too slow for packet switched optical networks. Generally, the choice between different light sources depends upon the applications, tuning time and tuning range.

1.5.2. Tunable Filters

A tunable optical filter is also one of the important parts of the optical network. Many promising approaches have been studied including Fabry-Perot, acousto-optic, electro-optic and liquid crystal Fabry-Perot filters [8, 10]. The filters have two important parameters dealing with the performance: tuning range and tuning time. The tuning ranges are from around 10 nm up to 500 nm, while the tuning time is from few nanoseconds up to 10 milliseconds.

1.5.3. Optical Cross-Connects/Switches

The optical switch or Optical Cross-Connect (OXC) is a device which can dynamically be configured to connect the given input ports to any of the output ports. The optical switches can be classified according to their flexibility:

1. A *non-blocking switch* means any connection pattern can be realized by reconnection of some or all of the current connections.
2. *Wide-sense non-blocking switch* is a switch which can be configured to add any new connections without interrupting previously configured connections through the switch.
3. *Strict-sense non-blocking switch* on the other hand can be defined as that switch which can add new connections any time without interrupting any of the current connections.

Clearly the number of elements and device complexity grows at the same time. This means a trade-off between hardware complexity and management complexity is to be made.

1.5.4. Components of Wavelength Routed Networks

In WDM-networks each fiber contains W wavelength channels and thus the optical switches should be capable to treat channels individually. The optical cross-connects used in WDM-networks can be divided into two categories [10]: wavelength selective cross-connect (WSXC) and wavelength interchange cross-connect (WIXC). A wavelength selective cross-connect is a device capable of configuring any given input λ-channel from arbitrary input port to a given output port (using the same wavelength). *Wavelength translation* (conversion) is an operation where an incoming signal using λ_1-channel is converted to another channel λ_2 at the output port. Wavelength interchange cross-connect as depicted in figure (1.4), is a more advanced device than WSXC which can manipulate wavelengths of the signals as well, i.e. an incoming signal can emerge from the switch using another wavelength. Hence, such a device can configure λ_1-channel from any input port to any output port using λ_2-channel, i.e. it is capable of doing wavelength translations as well. Clearly, a WIXC device is not only more complex than WSXC, but it also gives more flexibility in the configuration of the network and hence leads to more efficient use of the network resources. Both the WSXC and WIXC are devices where every input channel is connected to not more than one output-channel (permutation switch).

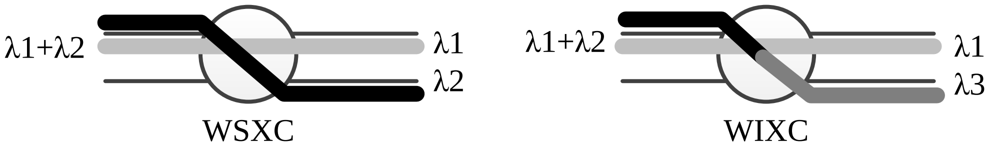


Figure 1.4: The basic components of the wavelength routed network (WSXC & WIXC)

1.5.5. Wavelength Converters

Wavelength conversion is a process of converting the signal from one wavelength on an incoming link to a different wavelength on an outgoing link and wavelength converters are devices which are used to perform these wavelength conversions. Wavelength conversion allows more efficient use of the network resources and without wavelength conversion the so called wavelength-continuity constraint has to be satisfied, i.e. the lightpath reserves the same wavelength all the way along the route. Hence, even if there are free channels available on every link of the network, some connections may not be configured unless wavelength conversion is possible in some of the nodes. Again, an easy solution is to do the opto-electronic wavelength conversion where the optical signal is first converted to the electrical domain and then reproduced in the optical domain at a different wavelength. This helps to improve the wavelength reuse in which wavelength can be spatially reused to carry different connections on different fiber links in the network. The drawback with this approach is the limited bit rate of electronics. There are four types of wavelength conversion: full wavelength conversion, limited wavelength conversion, fixed conversion and partial wavelength conversion. In full conversion any incoming wavelength can be shifted to any outgoing wavelength, while in limited conversion not all incoming channels can be connected to all outgoing channels. In fixed conversion each incoming channel may only be connected to one or more predetermined channels. In partial wavelength conversion, different nodes in the network can have different levels of wavelength conversion capability [11]. Another approach is to do the conversion in the optical domain. Suggested solutions include using the four-wave mixing, fiber nonlinearities and cross modulation with active semiconductor devices. An up-to-date survey on wavelength conversion can be found in [9].

1.5.6. Optical Amplifiers

The attenuation of optical signals is low in comparison to electrical signals. Still there is a possibility that long-distance links may require amplifiers in order to operate properly. The optical signal loses its energy because of transmission impairments in a fiber. Long distance optical transmission is possible only by signal amplifiers that provide a power boost to the signals. The traditional way to solve this problem is to convert the signal back to electrical domain for amplification and retransmit it optically. This approach requires knowledge of used bit rate and modulation. A new solution is to use amplifiers operating totally in optical domain. This solution is called Optical Amplifiers. Optical amplifiers can be placed in three different positions in a link. *Power amplifier* is placed at the beginning of a link to give a power boost to the clear signal. *Pre amplifier* is placed before the receiver and *line amplifier* is placed in the fiber. The three types of amplifiers which are mostly used are Semiconductor Optical Amplifiers (SOA), EDFA and Raman Amplifiers. Each of these types has specific spectral range and amplification gain. In particular, EDFA operating at 1540 nm region has proved to be an excellent choice for WDM systems. The amplifier is transparent to coding, bit-rate and thus suits well to all-optical framework. The gain of EDFA is between 25-51 dB and its spectral range is 35 nm around 1550 nm. A recent technology uses a circuit of EDFAs to fully exploit the spectrum of all-wave fiber and it is called *ultra wide-band* EDFA [10].

1.6. Technology in today’s era

In the field of data communications things changes rapidly; what is the state of today’s technology will probably be the old technology of tomorrow. This section will serve as a background for the stochastic models and optimization techniques.

1.6.1. Internet Protocol

The Internet Protocol (IP) has been a massive success story during the last twenty years. The dawn of the internet was back in the 70’s when Arpanet was created. Arpanet was funded by Defense Advanced Research Projects Agency (DARPA), the agency of U.S. Department of Defense (DoD) in charge of advanced research projects. Since then the internet has grown to a worldwide network and the number of computers connected to it has also grown extremely fast. Nowadays, the internet standards are defined within the Internet Engineering Task Force (IETF) which coordinates the standardization work in the internet community. The Requests for Comments (RFC) form the backbone of documents and describes how things are to be done on the internet. The IP defines a packet based way to communicate over a heterogeneous environment including slow modem links as well as high capacity backbone routes. Generally, IP network is a best effort network with no guarantee for any Quality of Service (QoS). The related layer 4 protocols are Universal Datagram Protocol (UDP) and Transmission Control Protocol (TCP) which are built upon the internet protocol. The UDP is a connectionless protocol to send an IP packet. Nothing is guaranteed, the packet may be lost without any feedback. It is left to the application to solve the possible problems. The TCP on the other hand is a connection oriented protocol where the stream of bytes is guaranteed to reach the destination in the correct order (or the failure is reported to both the ends). TCP/IP also includes mechanisms for congestion control with slow start, where the transmission rate is slowly increased until a packet is lost and the transmission speed is cut to half. Hence, TCP/IP is scalable to different transmission speeds. Many of the current popular applications including E-mail, WWW, ftp and telnet rely on TCP/IP, while UDP is used in some applications like Network File System (NFS) and real-time applications.

1.6.2. SDH and SONET

SDH stands for the Synchronous Digital Hierarchy and is widely used transmission system in Europe. SONET, Synchronous Optical Network is its American counterpart.

SDH is defined by the European Telecommunications Standards Institute (ETSI), while the SONET is defined by the American National Standards Institution (ANSI). These standards define the line rates, coding schemes, bit-rate hierarchies, restoration and network management. Equipment from different vendors can be used together and network operators get more freedom in building their networks. Both systems use a small time frame containing header and a payload as a basic building block. Higher transmission rates are obtained by byte-interleaving the basic time frames. Almost all of the processing is done digitally. Optical signals in SONET are denoted with OC-*x*, where *x* defines the bit-rate. For example, OC-48 signal means 2.5 Gbit/s and OC-192 signal corresponds to about 10 Gbit/s transmission speed. The SDH counterparts for the OC-signals are STM-signals where STM-1 designates transport rate of 155.52 Mbps and other STM-4, STM-16 and STM-64 have similarly 4, 16 and 64 times higher transmission speed than the STM-1 signal. Thus, STM-64 and OC-192 both have a transmission rate of 10 Gbps.

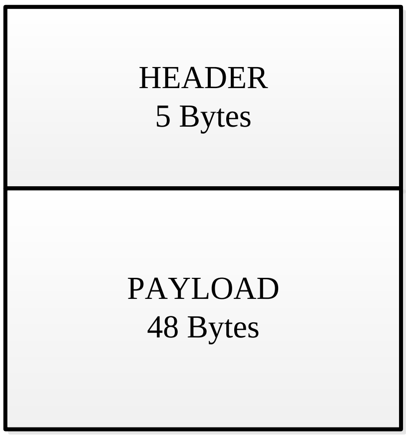


Figure 1.5: An ATM-cell

1.6.3. Asynchronous Transfer Mode

The Asynchronous Transfer Mode (ATM) has received a lot of research interest during the last few years. It is a cell-oriented switching and multiplexing technology. In the ATM concept the basic building block is a 53-byte long cell divided into 5 bytes long header and 48 bytes long payload as shown in figure (1.5). Originally, ATM was developed to support different kind of traffic (service classes) with different QoS requirements and intended to be used up to the end nodes, but currently it is mainly used in the backbone networks. ATM is a *connection oriented* network technology, i.e. the connections must be set up before the information can be transferred and afterwards the connection is released. The two important concepts with ATM technology are Virtual Paths (VP) and Virtual Channels (VC). The virtual paths are used to form a virtual topology over the physical ATM network. Each virtual path carries one or more virtual channels which are statistically multiplexed in the virtual path.

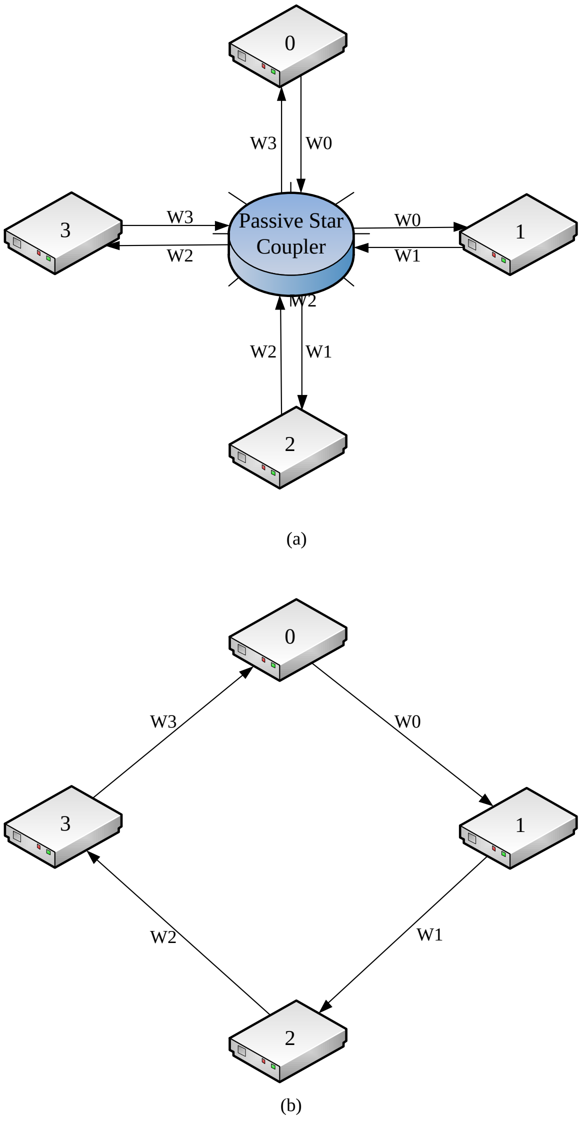
1.7. WDM Optical Network Architectures

There are three classes of WDM optical network architectures: broadcast-and-select network, wavelength routed networks and linear lightwave networks.

1.7.1. Broadcast-and-Select Networks

Passive star coupler is the main part of a broadcast-and-select network which connects the nodes in the network as shown in figure (1.6). Each node is composed of one or more fixed-tuned or tunable optical transmitters and one or more fixed-tuned or tunable optical receiver. Different messages are transmitted simultaneously on different nodes. These messages are then combined by star coupler and are then broadcasted to all nodes. A desired wavelength is selected by every node to receive the desired message by tuning its receiver to that wavelength. The star coupler offers an optical equivalence to radio systems: each transmitter broadcasts its signals or messages on different wavelengths and receivers are tuned to receive the desired signals.

In single-hop broadcast-and-select network, a message once transmitted as light reaches its final destination directly without being converted to electronic form in-between. In order to support packet switching in these networks rapid tuning of optical transmitters and receivers is required. This is because, in a packet-switched network a node must be able to transmit (receive) successive packets to (from) different nodes on different wavelengths. In these networks the main networking challenge is the coordination of transmissions between various nodes. In the absence of coordination or efficient Medium Access Control (MAC) protocol, collision occurs when two or more nodes transmit on same wavelength at the same time. Also, destination conflict occurs if two or more nodes transmit on different wavelengths to the same destination when the destination has only one tunable optical receiver. Moreover, the destination must know when to tune the appropriate wavelength for reception of a packet. Several MAC protocols have been processed to prevent such collision/conflicts for single-hop broadcast-and-select networks assuming the availability of rapidly tunable transmitter and/or receivers [10].



(a)

(b)

Figure 1.6(a): Broadcast-and-select network. **(b):** Logical topology

To support the packet switching efficiently in broadcast-and-select networks, a multi-hop approach which avoids rapid tuning altogether can be used. Each node has a small number of fixed-tuned optical transmitter and fixed-tuned optical receivers and each transmitter is tuned at different wavelength. We can represent the network as a graph, where a node corresponds to a network node and an edge corresponds to a transmitter-receiver pair on the same wavelength. Thus, we obtain a *virtual* or *logical topology* over the physical broadcast topology. Figure (1.6(a)) shows a four node broadcast-and-select network. Each node transmits at one fixed wavelength and receives on other fixed wavelength. For example, node 0 can transmit directly to node 1 using wavelength w_0 but not to node 2. To transmit to node 2, node 0 sends a packet to node 1 on wavelength w_0 which receives it, converts it to electronic form and retransmits it on wavelength w_1.

The packet then reaches node 2. The virtual topology of the network in figure (1.6(a)) is shown in figure (1.6(b)). In these networks a packet may have to go through more than one hop before reaching its destination. This leads to an increase in propagation delay in addition to queuing delay at intermediate nodes and wastage of network capacity. The advantage of broadcast-and-select networks is their simplicity and natural *multicasting* capability (ability to transmit the message to multiple destinations). However, there are severe limitations.

1) They require a large number of wavelengths typically at least as many as there are nodes in the network because there is no wavelength reuse in the network. Thus the networks are not scalable beyond the number of supported wavelengths.
2) They cannot span long distances since the transmitted power is split among various nodes and each node receives only a small fraction of the transmitted power, which becomes smaller as the number of nodes increases.

For these reasons the main application for broadcast-and-select is high-speed Local Area Network (LAN) and Metropolitan Area Network (MAN).

1.7.2. Linear Lightwave Networks

A usable portion of optical spectrum can be divided into a number of either wavelengths or wavebands. Wavebands are further subdivided into a number of wavelengths. The sufficient spacing or guard bands have to be placed between any two wavelengths to allow for imprecision and drift in laser transmitter tuning and to make it possible to separate adjacent signal at the receivers. Wavelength-routed network use wavelength partitioning and in these networks several wavelengths are multiplexed on a fiber link. Linear lightwave networks on the other hand use waveband partitioning and in these networks several wavelengths are multiplexed on each waveband and several wavebands are multiplexed on a fiber. A linear lightpath network as a whole does not distinguish between wavelengths within a waveband; individual wavelengths within a waveband are separated from each other at the end nodes. Two constraints – wavelength continuity and distinct wavelength assignment on optical connection are applicable to both wavelength routed networks and linear lightwave networks.

1.7.3. Wavelength Routed WDM Optical Network

Wavelength-routed WDM optical network have the potential to avoid three problems – lack of wavelength reuse, power splitting loss and scalability to Wide Area Networks (WANs); which are present in case of broadcast-and-select networks. A wavelength routed network consists of routing nodes (WXC) interconnected by point-to-point fiber links in an arbitrary topology. Each end node (end user) is connected to a WXC via an optical fiber link. The combination of end node and its corresponding WXC is referred as a network node. Each node is equipped with a set of transmitters and receivers for sending data into the network and receiving data from the network respectively, both of which may be wavelength-tunable.

In a wavelength routed network a message is sent from one node to another node using a wavelength continuous route called a *lightpath*, without requiring any optical-electronic-optical conversion and buffering at the intermediate nodes. This process is known as *wavelength routing*. The intermediate nodes route the lightpath in the optical domain using their WXCs. The end nodes of the lightpath access the lightpath using transmitter/receiver that is tuned to the wavelength on which the lightpath operates. A lightpath is an *all-optical communication path* between two nodes established by allocating the same wavelength throughout the route of transmitted data. Thus, it is a high-bandwidth pipe carrying data up to several gigabits per second and is uniquely identified by a physical path and a wavelength. The requirement that the same wavelength must be used on the entire selected route is known as the *wavelength continuity constraint*. Two lightpaths cannot be assigned the same wavelength on any fiber. This requirement is known as *distinct wavelength assignment constraint*. However, two lightpaths can use the same wavelength if they use disjoint set of links. This property is known as *wavelength reuse*. Wavelength reuse is an important feature that refers to simultaneous transmission of message on the same wavelength over fiber-link disjoint lightpaths. This feature of wavelength routed network makes them more scalable than broadcast-and-select networks. Another important characteristic which enable wavelength-routed networks to span long distance is that the transmitted power invested in the lightpath is not split to irrelevant destinations.

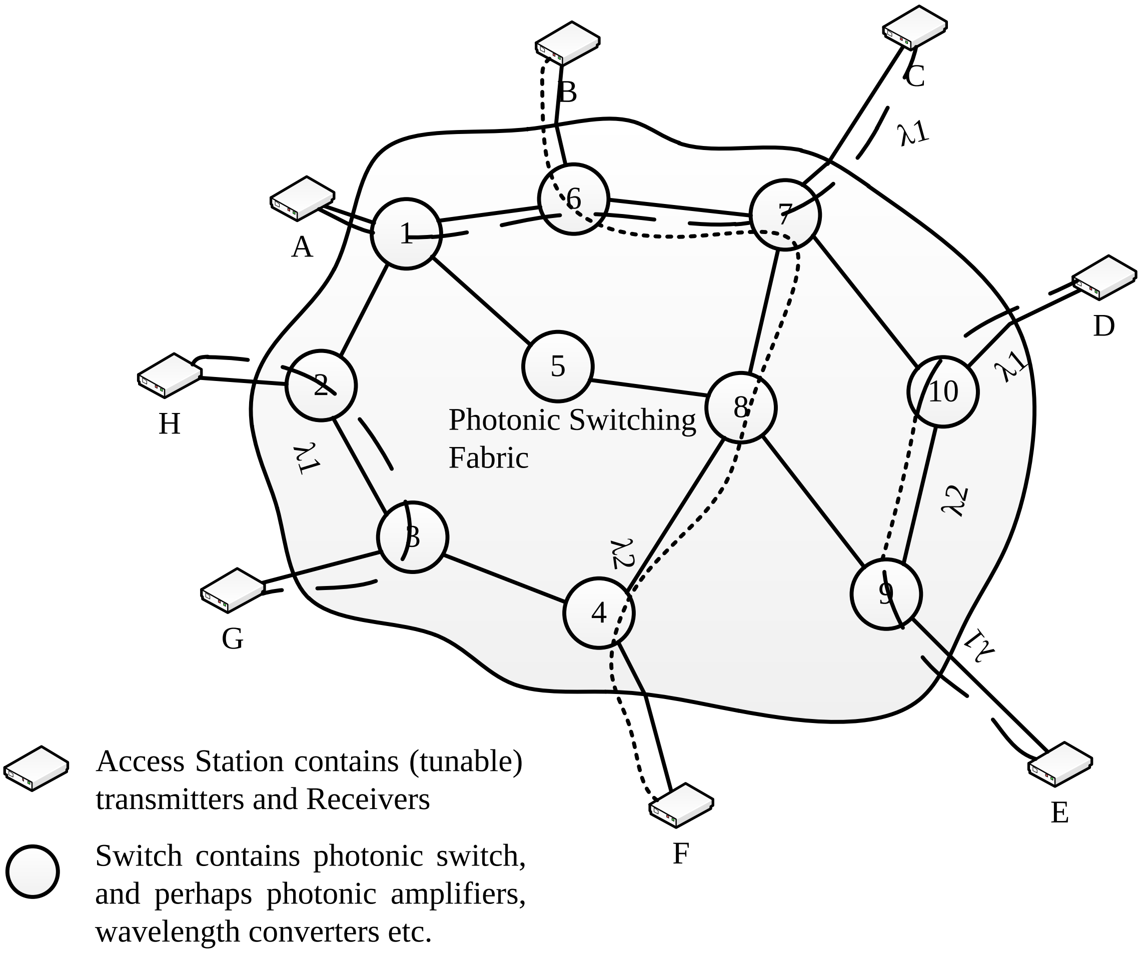


Figure 1.7: A wavelength-routed optical WDM network

A wavelength-routed optical WDM network is shown in figure (1.7). The network consists of an *optical switching fabric* [6], comprising active switches connected by fiber links to form an arbitrary *physical topology*. Actually, each switching node may support multiple end-users. Each node is equipped with a set of transmitters and receivers both of which may be wavelength tunable. A transmitter at a node sends data into the network and a receiver receives data from the network. The basic mechanism of communication in a wavelength-routed network is a lightpath. A lightpath is an optical communication channel between two nodes in the network and it may span for more than one fiber link. The intermediate nodes in fiber path route the lightpath in optical domain using their active switches. The end-nodes of the lightpath access lightpath with transmitters and receivers that are tuned to the wavelength on which that lightpath operates. For example in figure (1.7) the lightpaths are established between nodes A and C on wavelength channel λ_1, between B and F on wavelength channel λ_2 and between H and G on wavelength channel λ_1. The lightpath between node A and C is routed via active switches 1, 6 and 7. In the absence of any wavelength-conversion device a lightpath is required to be on the same wavelength channel throughout its path in the network. This requirement may not be necessary if we have wavelength converters in the network. These attractive features – wavelength reuse, protocol transparency and reliability – make wavelength routed networks suitable for WANs.

One of the important requirements in control plane of a wavelength-routed optical network is to set up and take down optical connections which are established by lightpaths between source and destination nodes. When the wavelength conversion is not possible at intermediate routing nodes a lightpath must occupy the same wavelength on each link over its physical route. This restriction is known as the wavelength-continuity constraint [12]. Wavelength continuity constraint is an important constraint which uses same wavelength on every link of the path to make a lightpath. This is true when OXCs in wavelength-routed optical network do not have wavelength conversion capability. On the contrary, when lightpath allocation is done link by link so that end-to-end optical path is a chain of lightpaths of different wavelengths. It is called a *virtual wavelength path* (VWP) (or *semi-lightpath*). This is a consequence of the fact that OXCs in wavelength-routed optical network provide the additional facility of wavelength conversion. We distinguish between static and dynamic lightpath depending upon the nature of traffic load in the network. When nature of the traffic pattern is static, a set of lightpath is established all at once that remain in the network for a long period of time. Such static lightpath establishment is relevant in the initial design and planning stage and the objective is to maximize the network throughput. For dynamic traffic scenario where traffic pattern changes rapidly, the network has to respond to the traffic demand quickly and economically. In such a dynamic traffic case, a lightpath is set up for each connection request as it arrives and lightpath is released after some finite amount of time. This is called *Dynamic Lightpath Establishment* (DLE). Given a WDM network, the problem of routing and assigning wavelength to lightpaths is of paramount importance in these networks. The clever algorithms are needed in order to ensure that Routing and Wavelength Assignment (RWA) function is performed using a minimum number of wavelengths. The number of available wavelengths in a fiber link plays a major role in these networks which is increasing day by day.

Packet switching in wavelength routed networks can be supported by using either a single-hop or a multi-hop approach, in a way similar to broadcast-and-select networks. In the multi-hop approach, a virtual topology (a set of lightpaths or *optical layer*) is imposed over the physical topology by setting WXCs in the nodes.

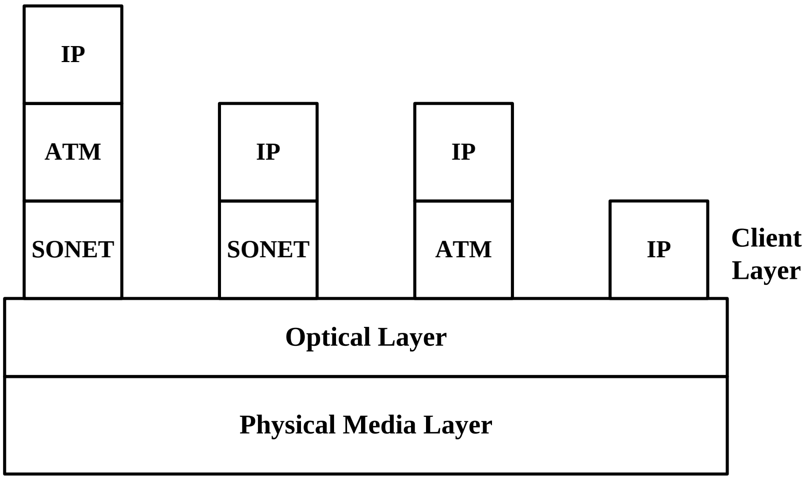


Figure 1.8: Possible layers in a WDM optical transport network

Existing internet backbone network consist of high-capacity IP routers interconnected by point-to-point fiber links. Traffic is transported between routers through high-speed gigabit links. These links are realized by SONET or ATM-over-SONET technology. The backbone routers are IP-over-SONET or IP-over-ATM-over-SONET technology to route IP traffic in backbone network. Most of the SONET-based backbone transport networks provide data interface at the rate of OC-3 and OC-12. The traffic demand is growing at a faster rate and a point has been reached where the data interfaces at the rate of OC-48 and more are required. Upgrading the existing SONET transport infrastructures to handle these high-capacity interface rates is not desirable as it is impractical to go for upgrading every time the interface rate increases. Also, such upgrading is not economical. A viable and cost-effective solution is to use WDM technology in backbone transport networks. In IP-over-WDM networks, network nodes are interconnected by WDM fiber links and those nodes employ WXCs and electronic processing elements. In a typical WDM backbone network, the electronic processing element can be an IP route, ATM switch or a SONET system. Any two IP routers in this network can be connected together by a lightpath. Two nodes that are not connected directly by a lightpath communicate using multi-hop approach, i.e., by using electronic packet switching at the intermediate nodes. The electronic packet switching can be provided by IP routers, ATM switches or SONET equipment leading to an IP-over-WDM or an ATM-over-WDM or a SONET-over-WDM network respectively.

A WDM-based transport network can be divided broadly into three layers; *a physical layer, an optical layer and a client layer* as shown in figure (1.8). Application of WDM technology has introduced an optical layer between lower physical medium layer and upper client layer. A set of lightpaths constitutes the optical layer (virtual layer). The optical layer provides client-independent or protocol-transparent client-switched service to a variety of clients that constitute the client layer. Thus the optical layer can support a variety of clients concurrently. A network with optical layer can be configured such that in the event of failures lightpaths can be rerouted over alternate paths automatically. This provides a high degree of reliability of the network. According to International Telecommunications Union–Telecommunication Standardization Sector (ITU-T) recommendation G.872, an optical layer can be further decomposed into three sub layers: *an optical channel layer, an optical multiplex section layer* and *an optical transmission section layer*. The functionality of the optical channel layer is to provide end-to-end networking of lightpaths for transparently conveying the client data. The optical multiplex section layer concerns networking of aggregate multi-wavelength optical signals. The optical transmission section layer concerns the transmission of optical signal on different kinds of optical media such as single-mode and multi-mode transmission.

1.8. Constraints in Wavelength Routed WDM Optical Networks

Some of the important issues in wavelength routed optical WDM networks include routing and wavelength assignment problem as a single complete problem, wavelength routing and rerouting problem, wavelength assignment, connection request, minimizing the effect due to wavelength continuity constraint, design, reconfiguration, survivability, traffic grooming, minimization of blocking probability, improvement of fairness, wavelength conversion and IP-over-WDM.

1.8.1. Routing and Wavelength Assignment problem

Sitting in the heart of WDM is the *routing and wavelength assignment* problem [10]. The problem of routing and wavelength assignment is crucial in wavelength routing networks. RWA is the unique feature of WDM networks in which lightpath is implemented by selecting the path of a physical link between source and destination edge nodes and reserving a particular wavelength on each of these links for the lightpath. Thus for establishment of an optical connection, one must deal with the selection of the path (Routing problem) as well as allocating the available wavelengths for the connections (Wavelength Assignment problem). This resulting problem is known as *routing and wavelength assignment* problem. This problem can be defined as; *given the network topology and a set of end-to-end lightpath requests, determine a route and wavelength(s) for the requests, using the minimum possible number of wavelengths* [4, 13].

Routing and wavelength assignment is critically important to increase the efficiency of optical networks [14]. Connection requests may be of three types: static, incremental and dynamic. With static traffic, the entire set of connections is known in advance and then the problem is to set up lightpaths for these connections in a global fashion while minimizing network resources utilization such as number of wavelengths or number of fiber links in the network. In incremental traffic case connection requests arrive sequentially, a lightpath is established for each connection and the lightpath remains in the network indefinitely. In case of dynamic traffic a lightpath is set up for each connection request as it arrives and lightpath is released after some finite amount of time. The objective in this incremental and dynamic traffic cases is to set up lightpaths and to assign wavelengths in a manner that minimizes the amount of connections blocking or maximizes the number of connections that are established in the network at any time. This problem is referred as dynamic lightpath establishment problem. It can easily be shown that the optimal RWA problem is NP-complete by using results of [13] on Static Lightpath Establishment (SLE) and by restricting the general problem to tree topologies. An integer programming formulation of the optimal RWA problem in the presence of deterministic traffic can be found in [15], while in [16] a similar formulation combined with randomized rounding has been presented.

In wavelength routed WDM networks a connection is realized by a lightpath. In order to establish a connection between a source-destination pair a wavelength continuous route needs to be found between the node pair. An algorithm used for selecting routes and wavelengths to establish lightpaths is known as routing and wavelength assignment algorithm. In literature there are two methods to tackle the RWA problem. One of them is by taking routing and wavelength assignment as two separate problems [16-20] i.e. routing problem and wavelength assignment problem and the other method is by taking routing and wavelength assignment problem as a single problem [21-23].

1.8.2. Static Verses Dynamic RWA

In a wavelength routing network, the connection request (traffic demand) can be considered either *static* or *dynamic*, it can be said that lightpath requests can be either *offline* or *online* respectively. In case of a static RWA connection requests are known as a *priori* [24, 25]. The traffic demand may be specified in terms of source-destination pairs. These pairs are chosen based on an estimation of long-term traffic requirement between the node pairs. In a static traffic pattern (offline lightpath requests) a set of lightpaths are set up all in advance and remain in the network for long time; they can be considered *permanent*. The RWA problem is known as *offline RWA* in this case. The objective is to assign route and wavelengths to all demands so as to minimize the number of wavelengths used. The dual problem is to assign route and wavelengths so as to maximize the number of demands satisfied for a fixed number of wavelengths. The above problems are categorized under SLE problem. The SLE problem has been shown to be NP-complete (i.e. it is computationally intractable or, in other words, the only known algorithms that find an optimal solution require exponential time in the worst case) [26]. Therefore, polynomial-time algorithms which produce solutions close to the optimal one are preferred.

In case of dynamic RWA, connection requests arrive and depart from a network one by one in a random manner. The lightpaths once established remain for a finite time. In a dynamic traffic pattern a lightpath is set up for each connection request as it arrives and lightpath is released after some finite amount of time. The lightpaths are switched in this case and are then provided in a circuit-switched fashion. The RWA problem here is called online RWA. It may become necessary to tear down some existing lightpaths and establish new lightpaths in response to changing traffic patterns or network component failures. Unlike static RWA problem any solution to dynamic RWA problem must be computationally simple as the requests need to be processed online. When a new request arrives, a route and wavelength needs to be assigned to the request with an objective of maximizing the number of connections requests honoured (equivalent to minimizing the number of connection requests rejected).

1.8.3. Solution to RWA Problem

A good RWA algorithm is critically important to improve the performance of wavelength-routed WDM networks. In [27], a heuristic RWA algorithm has been proposed to maximize the carried traffic (or equivalently minimizing the blocking probability) when the connection requests arrive dynamically. Solutions based on approximation techniques should be proposed as proposed in [16], for the RWA problem with an objective of minimizing the number of wavelengths required in both the SLE and DLE cases. We can divide this problem in two problems namely; routing problem and wavelength assignment problem and then we can propose different solutions to this problem.

1.8.4. Wavelength Assignment and Conversion schemes

There are two constraints that have to be kept in mind by the approaches when trying to solve RWA. In fact the constraints concern the second part of the problem, in which routes of lightpaths are assumed to be known in advance and what remains to be done is *wavelength assignment* (*WA*). The constraints are summarized below:

i. *Distinct wavelength assignment constraint*: All lightpaths sharing a common fiber must be assigned distinct wavelengths to avoid interference. This applies not only within the all-optical network but in access links as well.

ii. *Wavelength continuity constraint*: The wavelength assigned to each lightpath remains the same on all the links it traverses from source end-node to destination end-node.

The first constraint holds for solving wavelength assignment problem in any wavelength routing network. The second constraint applies only to the simple case of wavelength routing networks that have no wavelength conversion capability inside their nodes. Wavelength assignment is a unique feature in wavelength routed networks that distinguishes them from conventional networks.

Based on the order in which the wavelengths are searched, wavelength assignment methods are classified into *most-used, least-used, fixed-order* and *random-order* [21, 22 and 28]. In the most-used wavelength assignment method, wavelengths are searched in non-increasing order of their utilization in network. This method tries to pack the lightpaths so that more wavelength continuous routes are available for the request that arrives later. In the least used wavelength assignment method, wavelengths are searched in non-decreasing order of their utilization in the network. This method spreads the lightpaths over different wavelengths. The idea here is that a new request can find a shorter route and a free wavelength on it. The argument is that the most-used wavelength assignment method may tend to choose a longer route as it always prefers the most-used wavelength. In the fixed-order wavelength assignment method, the wavelengths are searched in a fixed order. The wavelengths may be indexed and the wavelength with the lowest index is examined first. In the random wavelength assignment method the wavelength is chosen randomly from the free wavelengths. The most-used and least-used wavelength assignment methods are preferred for networks with centralized control. The other two methods are preferred for the networks with distributed control. The numerical results reported in literature show that the most-used wavelength assignment method performs better than the least-used method and the fixed-order wavelength assignment method performs better than the random method.

One possible way to overcome the bandwidth loss caused by the wavelength continuity constraint is to use wavelength converters at the routing nodes. A wavelength converter is an optical device which is capable of shifting one wavelength to another wavelength [28, 29]. The capability of a wavelength converter is characterized by the degree of conversion. A converter which is capable of shifting a wavelength to any one of D wavelengths is said to have conversion degree D. The cost of a converter grows with the increasing conversion degree. A converter is said to have full degree of conversion when the conversion degree equals the number of wavelengths per fiber link. Otherwise, it is said to have partial or limited degree of conversion.

The basic function of the wavelength converter is to convert an input wavelength to possibly different output wavelengths within operational bandwidth of WDM systems in order to improve their overall efficiency and hence the reuse factor is increased. Wavelength converters are one of the important building blocks of any WDM system as they enable reuse of wavelengths in that system. This process is needed in order to increase the overall system bandwidth and for wavelength routing. There are four possible forms of waveform conversion: full conversion, limited conversion, fixed conversion and sparse wavelength conversion. In full conversion type, any wavelength shifting is possible and therefore channels can be converted regardless of their wavelengths. In the limited conversion type, wavelength shifting is restricted so that not all combinations of channels may be connected. In the fixed conversion each channel may be connected to exactly one predetermined channel on all other links. Finally, in the sparse wavelength conversion, networks are comprised of a mixture of nodes having full and no wavelength conversion. An ideal converter has the characteristics such as [4, 10, 18, 30, 31, and 32]: transparent to bit rates and signal formats; ability to convert to both short and longer wavelength; has fast set-up time; has low chirp output and high signal-to-noise ratio; simple to implement; polarization insensitivity; straightforward implementation.

Due to multi-wavelength fiber optic systems interest is growing in converting signals from one wavelength to another. The simplest method to convert wavelengths today is opto-electronically where input signal is converted to electronic form and then it is used to modulate a transmitter operating at desired wavelength. This process is common these days wherever wavelengths must be converted but like electro-optical repeaters it is cumbersome and inefficient. In order to convert the wavelength we need a complete receiver-transmitter set. It would seem better to convert wavelengths by purely optical means but that is difficult in practice. However, this is changing as we start to see new developments in this area. New schemes for wavelength conversion in the optical domain have been developed recently. One approach is to use a process like four-wave mixing. In this case, we combine the input signal with light at another wavelength to generate a different wavelength. A second approach is to use light at one wavelength to control a semiconductor laser operating at another wavelength. The input light changes population of current carriers in the laser leading to modulation of its output. Although simple in concept it turns out to be difficult in practice. A third scheme is to build an optically controlled gate which is essentially a modulator controlled by the input of light rather than by a voltage signal. It directly modulates a laser output or controls an external modulator that modulates another laser.

A WXC having one or more wavelength converters is called as a wavelength interchange cross connect. A node with wavelength conversion capability is called a Wavelength Converting (WC) node or a Wavelength Interchange (WI) node. A WDM network with WC node is called wavelength-convertible network. A node may have a maximum of F_{in} x W converters, where F_{in} is the number of full-degree converters, its performance reaches the best achievable. Since wavelength conversion is an immature extremely costly technology, it may not be economical to install wavelength converters at every node of a network. Rather, it may be more sensible to put wavelength converters at some but not all nodes in the network called *sparse wavelength conversion network* [33].

1.8.5. Wavelength Routing and Rerouting Techniques

There are a number of wavelength routing techniques proposed in literature. The important routing schemes considered in literature [16, 20-22, 29] are *fixed routing*, *alternate routing* and *exhaust routing*. In the *fixed routing scheme* only one route is provided for a node pair. Usually this route is chosen to be the shortest route. When a connection request arrives for a node pair the route fixed for that node pair is searched for the availability of a free wavelength. In the *alternate routing scheme* two or more routes are provided for a node pair. These routes are searched one by one in a predetermined order. Usually, these routes are ordered in non-decreasing order of their hop length. In the *exhaust routing scheme* all possible routes are searched for a node pair. The network state is represented as a graph and a shortest-path-finding algorithm is used on the graph. While the exhaust method yields the best performance when compared to the other two methods, it is computationally more complex. Similarly, the fixed routing method is simpler than alternate routing method but it yields poorer performance than the other. In [34, 35], fixed routing, fixed alternate routing and some heuristics for wavelength assignment schemes have been proposed with the objective of minimizing the blocking probability for dynamically establishing lightpaths in response to a random pattern of arriving connection requests and connection holding times.

Apart from wavelength conversion and space division multiplexing there is yet another method to reduce the bandwidth loss caused by the wavelength continuity constraint in wavelength routed networks called *wavelength rerouting*. With wavelength converters employed in a network a lightpath needs to be wavelength-continuous between two consecutive converting nodes only. With space division multiplexing the chance of finding a wavelength-continuous route is enhanced as the same wavelength is available on every fiber on a link. Wavelength rerouting creates a wavelength-continuous route by migrating a few existing lightpaths to new wavelengths without changing their route.

Rerouting is a concept which was originally introduced in the design of circuit-switched telephone networks [36, 37]. This is simply the action of switching an existing lightpath or connection from one route to another route without changing the source and destination. It has also been applied to optical WDM networks recently [24, 38-41]. A comprehensive survey of rerouting techniques can be found in [42]. Rerouting algorithms may generally be categorized as follows:

- Passive rerouting [37–39, 41]: only if the simple routing procedure fails the rerouting procedure tries to accommodate the new connection request by shifting/migrating some existing lightpaths/connections.
- Active rerouting [40]: the rerouting procedure is typically controlled by a timer and it periodically shifts/migrates existing lightpaths/connections to better routes.
- Lightpath level rerouting [37–40]: traffic of lightpaths at the full wavelength capacity granularity is rerouted.
- Connection level rerouting [41]: traffic of connections at different bandwidth granularities is rerouted.

The network performance can be measured by blocking probability, which is the statistical probability that a telephone connection cannot be established due to insufficient transmission resources in the network. Usually it is expressed as a percentage or decimal equivalent of calls blocked by network congestion during the busy hour. Erlang-B, also known as the Erlang loss formula, is a formula for calculation of blocking probability. It is derived from the Erlang distribution to describe the probability of call loss on a group of circuits. It is mainly used in planning telephone networks.

1.9. Objectives of the Thesis

Considering the above mentioned challenges the objectives of research were formulated which are listed as below:

1. To study and analyse the existing wavelength assignment algorithms and to develop new algorithm of wavelength assignment for better performance in wavelength division multiplexed networks.
2. To study and analyse the existing routing algorithms and to develop new effective routing algorithms for survivable wavelength division multiplexed networks.
3. To compare the newly developed routing and wavelength assignment algorithms with the existing routing algorithms in terms of blocking for wavelength division multiplexed network.

1.10. Contribution of Thesis

In this thesis, possible solutions to several critical problems affecting performance of wavelength division multiplexing such as blocking probability, routing problem, fairness of the network and wavelength assignment problem have been analysed and presented. The main contributions of this thesis are as follows:

To have better blocking performance and fairness of the network four mathematical models have been proposed and compared with conventional models. These models are low complexity mathematical models which are used for calculation and reduction of blocking probability of WDM optical networks for both wavelength convertible networks as well as for wavelength non-convertible networks. These mathematical models proposed have closed-form expression and do not require any simulated statistics, they have low implementation complexity and computation used is quite efficient. These models suggest us to choose the best path and appropriate number of free wavelengths in the network. These models were also used to evaluate blocking performance of any network topology (such as NSFnet) which can be useful to improve the performance of given network topology.

Two effective algorithms named Most Used Wavelength Conversion and First Fit Wavelength Conversion have also been proposed and the performance of these wavelength assignment algorithms has been evaluated in terms of blocking probability and fairness. The results of proposed algorithm have been compared with conventional wavelength assignment algorithms such as First-fit, Best-fit, Random and Most used wavelength assignment algorithms. These proposed approaches proved to be very effective for the minimization of blocking probability of optical WDM networks. The response of blocking probability of a network having 10 nodes and variable load for existing wavelength assignment algorithms have been analysed. Two new wavelength assignment strategies which used sparse wavelength conversion have been proposed which proved to be very effective as compared to the earlier algorithms in situations where mathematical model of the system cannot be changed.

Further, two wavelength routing algorithms named Shortest Path Wavelength Rerouting Algorithm and Lightpath Rerouting Algorithm for dynamic provisioning of lightpath have been proposed which proved to be very efficient in calculation and minimization of blocking probability and produced very effective results. To improve performance of all optical survivable WDM networks a technique based on wavelength rerouting has been applied. Also, these wavelength rerouting algorithm were employed on realistic WDM optical network topology to investigate blocking performance and resource utilization. The key advantages of these algorithms as compared to the other routing algorithms proposed in literature are that these algorithms are very simple and require less service disruption time.

Routing and wavelength assignment strategy has been dealt as a single problem. Different routing and wavelength assignment strategies have been proposed which were used to evaluate the blocking performance of realistic networks such as NSFnet and EUPAN network topology and hence used to improve its performance on the basis of blocking probability. Further, a problem of enhancing multiple-fault restorability in path protected wavelength–routed all optical WDM networks has also been discussed. Different mechanisms have been proposed which were used to combat multiple link failures such as; Fault Tolerant Routing and Wavelength Assignment Algorithm and Survivable Routing and Wavelength Assignment Algorithm. These algorithms have also been compared with algorithms mentioned in literature. The algorithms dealt with optical networks with multiple faults proved to be effective where varying load is applied to the nodes. These algorithms worked well when load applied to the nodes is varied from low to high. Two generic routing and wavelength assignment algorithms (GRWA-I and GRWA-II) have also been proposed for optimization and minimization of blocking probability. The implementation of these proposed algorithms have less complexity and the computation used in these algorithms is quite efficient. It is clear from the results that proposed algorithms are applicable to any network topology, easy to implement, faster to use still very efficient.

Thus the investigations carried out in thesis result in blocking free environment. The probabilistic mathematical models and algorithms proposed in thesis are very simple in operation and do not require any simulation statistics. The implementation of these models and algorithms requires less complexity and the computation used is also very effective.

1.11. Organization of the Thesis

The thesis has been organized into seven chapters. Contents of each chapter are briefly described as under:

The introduction of optical networks and wavelength division multiplexing has been covered in chapter I. After introducing WDM and its basic concepts detailed literature review has been covered in chapter II.

Chapter III is based on the mathematical models which have been proposed for WDM networks. Implementation of these mathematical models on realistic networks has also been shown.

Chapter IV deals with wavelength assignment problem in wavelength division multiplex networks. The wavelength assignment techniques have been presented and comparison of blocking probability of the system has been made for various wavelength assignment algorithms.

Chapter V presents and compares the routing strategies for survivable WDM Networks. Fault tolerant routing strategies have also been presented for the better performance of WDM Survivable networks.

Chapter VI pertains to study and development of new RWA algorithms by dealing this problem as a single problem. The comparison of the newly developed routing and wavelength assignment algorithms with existing routing and wavelength assignment algorithm has also been made. Further, different algorithms have been proposed for survivable networks.

Finally, chapter VII highlights the conclusions drawn, recommendations of the work and provides the future scope of this thesis.

CHAPTER II

LITERATURE SURVEY

In this chapter, we have studied and presented the comprehensive literature survey of various performance related issues of wavelength division multiplexing. In section 2.1, blocking probability has been covered. The mathematical models proposed in literature for calculation of blocking probability has also been covered in this section. In section 2.2, several wavelength conversion and wavelength assignment strategies are studied. In section 2.3, different routing and rerouting schemes for survivable networks are studied and described. Finally, in section 2.4, we have studied traffic grooming and RWA problem. In this section RWA is also discussed as a single complete problem.

2.1. Blocking Probability Calculations

Hiroaki Harai, *et. al.* [43], treated a performance optimization problem in all-optical networks. They studied blocking performance of the optical network and proposed a heuristic algorithm to minimize an overall blocking probability by properly allocating a limited number of nodes with wavelength conversion capability.

Kalyani Bogineni *et. al.* [44], introduced a performance modelling technique based on a semi-markov analytical model, which eliminated many of the unrealistic assumptions of past approaches to analytical modelling. The performance of the protocol was analysed using this analytical model and discrete-event simulation. The performance is evaluated in terms of network throughput, packet delay and control.

Jennifer M. Yates *et. al.* [45], examined the blocking performance of networks in which connections may be blocked due to either insufficient capacity or due to limitations in the transmission network. Analytical expressions and network simulations were used to examine blocking in networks, in which the quality of the received signal may be so poor that the connection is effectively blocked.

Brett Schein *et. al.* [46], developed a system model to approximate the blocking probability for both the fixed and reconfigurable systems. They also characterized the gain in traffic capacity that is configurable wavelength division multiplexed network offering over a fixed topology network where lightpath connections are fixed and cannot be changed.

Suixiang Gao *et. al.* [47], minimized the overall system blocking probability by studying the problem of placing a given number of converters in a general topology WDM network. The contributions of this work were: (1) formulation of success probability in a network as a polynomial function of the locations of converters; (2) proposal of an optimized model of the converter placement problem as the minimization of a polynomial function of 0–1 variables under a linear constraint so that standard optimization tool scan be employed to solve the problem and (3) design of a search algorithm that can efficiently find the optimal solution to the converter placement problem.

Wanjiun Liao *et. al.* [48], proposed a service differentiation scheme called Pre-emptive Wavelength Reservation Protocol (PWRP) to provide proportional quality of service for Optical-Burst-Switched (OBS) networks. In the context of service differentiation, traffic was divided into different service classes based on traffic characteristics. A service differentiation scheme then provides different degrees of resource assurance to different classes of traffic in proportion to their service classes. An analytical model was derived and simulations were conducted to evaluate the performance. The results showed that the approach performed better than existing mechanisms in terms of lower blocking probability and higher resource utilization.

Xi Yang *et. al.* [49], measured the network performance in terms of blocking probability, resource utilization and running times under different resource allocation and routing schemes. They addressed the placement of regenerators based on static schemes allowing for only a limited number of regenerators at fixed locations. They further proposed a dynamic resource allocation and dynamic routing scheme to operate translucent networks. This scheme was realized through dynamic ally sharing regeneration resources, including transmitters, receivers, electronic interfaces between regeneration and access functions under a multi-domain hierarchical translucent network model. An intra-domain routing algorithm, which took into consideration optical-layer constraints as well as dynamic allocation of regeneration resources was developed to address the problem of translucent dynamic routing in a single routing domain.

Chuan-Ching Sue [50], reduced the blocking probability by presenting a wavelength-routing scheme with spare reconfiguration to construct dependable all-optical wavelength-division-multiplexing networks. They developed a Spare Reconfiguration mechanism with Wavelength Reassignment (SR_WR) and Path Reassignment (SR_PR) to make the spare dynamic. The proposed wavelength routing with SR proceeds in three stages and has polynomial time complexity. Extensive simulation experiments were conducted on the NSFnet and the K5 fully connected network to investigate the performance of the proposed wavelength routing with SR.

Hai Le Vu *et. al.* [51], computed and derived the scalable approximations for blocking probability. They have also provided new loss models for Hybrid Optical Switch (HOS) combining optical circuit switching and optical burst switching. Exact blocking probabilities were computed when no priority was given to either circuits or bursts. The sensitivity of the analytical results to burst length and circuit holding-time distributions was quantified by simulation. It was demonstrated that how the proposed approximations can be used for multiplexing-gain evaluation of a hybrid switch.

Dongsoo S. Kim *et. al.* [52], introduced a split routing algorithm and it's blocking probability to enhance the routability of the high fan-out requests. They studied three-stage Clos switching networks for multicast communications in terms of blocking probabilities on a random traffic model. Even though the lack of multicast capability in the input-stage switches requires a prohibitively large number of middle switches to provide compatible requests with non-blocking paths. They also proposed a probabilistic model which gave an observation that the blocking probability decreases drastically and then approaches zero as the number of middle switches is far less than the theoretical bound. They also corroborate the analytical model by performing network simulations based on a random request generator and a random routing strategy.

Suresh Subramaniam *et. al.* [53], minimized the call-blocking probability by considering the problem of optimal placement of a given number of wavelength converters on a path. Using a simple performance model, they first proved that uniform spacing of converters is optimal for the end-to-end performance when link loads are uniform and independent; then they showed that significant gains are achievable with optimal placement compared to random placement.

Ling Li *et. al.* [54], studied blocking probability and presented two dynamic routing algorithms based on path and neighbourhood link congestion in all-optical networks. In such networks, a connection request encounters higher blocking probability than in circuit-switched networks because of the wavelength-continuity constraint. They have considered Fixed-Paths Least-Congestion (FPLC) routing in which the shortest path may not be preferred to use. Then they developed a new routing method; dynamic routing using neighbourhood information. It was shown by analysis and simulation methods that FPLC routing with the first-fit wavelength-assignment method performs better than the alternate routing method in mesh-torus networks (regular topology) and in the NSFnet T1 backbone network (irregular topology).

Gaoxi Xiao *et. al.* [55], studied blocking probability and proposed a set of algorithms for allocating Fixed Wavelength Conversion (FWC) in all-optical networks. They adopted the simulation-based optimization approach in which utilization statistics of FWC's were collected from computer simulations and then optimization was performed to allocate the FWC's. Extensive computer simulations were conducted on regular and irregular networks under both the uniform and non-uniform traffic.

Gagan L. Choudhury, *et. al.* [56], computed steady-state blocking probabilities for each class in product-form loss networks to cover general state-dependent arrival and service rates. They proposed an algorithm which was based on numerically inverting the generating function of the normalization constant.

Ellen Witte Zegura [57], evaluated blocking probability in generalized connectors by presenting an analytical model. Equations were derived for computation of blocking probability for the important class of series-parallel networks. Investigations were made on accuracy of the equations by comparing the blocking probability computed.

2.2. Wavelength Conversion and Assignment Strategies

Z. Zhang *et. al.* [19], presented a heuristic algorithm for effective assignment of a limited number of wavelengths among the access stations of a multi-hop network where the physical medium consists of optical fiber segments which interconnect wavelength elective optical switches.

Poompat Saengudomlert *et. al.* [20], developed an on-line wavelength assignment algorithm for a wavelength-routed WDM tree network. The algorithm dynamically supports all k-port traffic matrices among end nodes. Implementation of proposed wavelength assignment algorithm was also demonstrated using a hybrid wavelength-routed/broadcast tree with only one switching node connecting several passive broadcast sub-trees.

Anwar Alyatama [58], used random and first-fit wavelength assignment approach for presenting an approximate analytical method and evaluated the blocking probabilities in wavelength division multiplexing networks without wavelength converters. The new approach viewed the WDM network as a set of different layers (colours) in which, blocked traffic in one layer is overflowed to another layer. Analysing blocking probabilities in each layer of the network is derived from an exact approach. A moment matching method was then used to characterise the overflow traffic from one layer to another.

Junjun Wan *et. al.* [59], proposed a wavelength assignment algorithm, which was based on the method called Dynamic Preferred Wavelength Sets (D-PWS). Also, they described the basic architecture of the optical burst switching network based on Dynamic Wavelength Routing (DWR), under which the guarantee of the quality of service in the DWR-OBS network was discussed. Then they focused on two aspects: the transmission latency of the data packets and the blocking probability, which leads to a quantitative description of the transmission latency and the size of the edge node buffer.

I. Alfouzan *et. al.* [60], introduced two new wavelength assignment reconfiguration algorithms, the One-Directional Transfer (1DT) and the Two-Directional Transfer (2DT) algorithms. The simulation results for both these algorithms were shown to outperform the existing algorithms in terms of the trade-off.

F. Matera *et. al.* [61], showed how to obtain a wavelength assignment in a wide geographical transport network connecting the main cities of Europe, when all optical wavelength converters are introduced in the network nodes. They also reported an investigation on 40 Gb/s transmission performance in the presence of all optical wavelength converters based on four wave mixing in semiconductor optical amplifiers and on different frequency generation in periodically poled lithium niobate waveguides.

Abhisek Mukherjee *et. al.* [62], proposed a new wavelength conversion algorithm in a DWDM network using online routing. The model for the algorithm has been theoretically developed and the corresponding call connection probability has been calculated. The limitation on the number of wavelength conversions has been addressed by fixing the maximum number of wavelength conversions allowed for the transmissions of a single packet over the network.

P. Rajalakshmi *et. al.* [63], proposed a new wavelength assignment technique called wavelength reassignment algorithm in which when the new call gets blocked due to wavelength continuity constraint the already established calls were reassigned the wavelength, so as to create a wavelength-continuous route in order to accommodate the new call. During wavelength reassignment the routes for all calls remain the same, i.e. no rerouting was done. The problem of enhancing the blocking performance, in the circuit-switched wide-area optical wavelength-division multiplexed networks with no wavelength conversion at the nodes was also considered.

Mahesh Sivakumara *et. al.* [64], studied the effect of wavelength conversion on the blocking performance of connections with multiple rates. The blocking performance of the TDM wavelength routing network was evaluated through simulations.

Raja Datta *et. al.* [65], presented a wavelength assignment algorithm which was used for optimal assignment of a single wavelength to single-hop traffic in a tree topology. The work was further extended for the wavelength assignment in a general graph. This polynomial time algorithm gave an optimal solution to the routing and wavelength assignment problem in a tree topology.

Jianping Wang *et. al.* [66], studied the problem of wavelength assignment for multicasting in order to maximize the network capacity in all-optical wavelength-division multiplexing networks. Two efficient greedy algorithms were also proposed for general multi-hop networks. The objective of this work was to minimize the call blocking probability by maximizing the remaining network capacity after each wavelength assignment.

Nen-Fu Huang *et. al.* [67], proposed an efficient distributed Wavelength Reusing/ Migrating /Sharing Protocol (WRMSP) for the Dual Bus Lightwave Networks (DBLN). This protocol constituted of three efficient schemes for carrying out the wavelength reusing, migration and sharing respectively.

Arun K. Somani *et. al.* [68], addressed the wavelength assignment issues in interconnecting optical local area networks in which a wavelength could not be reused for local connections. Static and dynamic approaches for partitioning of wavelengths were analysed and compared by simulations for local and global traffic. Several dynamic wavelength assignment algorithms were also developed and architectural issues interconnecting optical networks were also discussed. The objective was the development of a simple yet accurate model to predict approximate blocking performance with an arbitrary number of LANs.

Raul Munoz *et. al.* [69], proposed wavelength assignment schemes for dedicated protection rings. A novel Generalized Multiprotocol Label Switching (GMPLS) based lightpath signalling and wavelength reservation schemes were also evaluated for Dedicated Protection Ring (DPRing)-based MANs. Performance evaluation has been carried out in a GMPLS-based test bed named ADRENALINE.

Jian Liu *et. al.* [70], proposed two different wavelength assignment algorithms for the network. These wavelength assignment algorithms were proposed for minimization of blocking probability of the network.

Nen-Fu Huang *et. al.* [71], proposed a wavelength reuse algorithm for WDM star networks. They also proposed a wavelength-reusable local lightwave network constituted of two interconnected WDM star networks. Based on this architecture, the lower bounds for the problems of minimizing the switching duration and the number of switching modes were derived.

Kuo-Chun Lee *et. al.* [72], developed wavelength assignment algorithms for hierarchical networks and wavelength-routing algorithms for arbitrary network topologies. Signal to noise ratio was also analysed for in-band/out-band WDM signals.

Milan Kovacevic *et. al.* [73], proposed the wavelength assignment algorithms for a given path which was used to minimize the number of wavelength changes. They also studied the benefits of electronic wavelength translation in optical networks.

D. Guo *et. al.* [74], presented an optimal wavelength assignment algorithm and three different adaptive wavelength routing algorithms. This wavelength assignment algorithm was used to minimize the number of wavelengths used in the network. The performance of these proposed algorithms was evaluated in terms of call blocking probability. They also presented a method for minimization of call blocking probability with a fixed number of transceivers per node. A scalable multi-hop WDM passive ring architecture for local area or metropolitan area networks was also presented.

H. Ghafouri-Shiraz *et. al.* [75], presented a series of wavelength optimization and wavelength assignment algorithms with the objective to optimize the number of required SONET add–drop multiplexers. The other objective of these algorithms was to minimize the number of wavelengths in both unidirectional and bidirectional rings under an arbitrary grooming factor. Both uniform and general non-uniform all-to-all network traffic were considered for these algorithms.

Guangzhi Li *et. al.* [76], studied the off-line wavelength assignment problem in star and ring networks for optical wavelength division multiplexed networks. The results showed that the ability to switch between fibers increases wavelength utilization. Additionally, the complexity of the problem was studied and several constrained versions of the problem were also considered for star and ring networks.

Xijun Zhang *et. al.*[77], proposed generic wavelength assignment algorithms for optical WDM networks. These proposed optimal or near-optimal algorithms for traffic grooming. The wavelength assignment algorithm was used to reduce the number of wavelengths and S-ADMs. They were applied to both unidirectional and bidirectional rings having an arbitrary number of nodes under both uniform and non-uniform traffic with an arbitrary grooming factor. Some lower bounds on the number of wavelengths and S-ADMs required for a given traffic pattern were derived and were used to determine the optimality of the proposed algorithms.

Zhenghao Zhang *et. al.* [78], studied on-line wavelength assignment in wavelength-routed WDM networks under both unicast and multi-cast traffic where nodes in the networks have wavelength conversion ability. They considered the nodes in the networks having only limited number of converters. They studied the problem of setting up connections in such networks using minimum number of wavelength converters.

Jianping Wang *et. al.* [79], studied wavelength assignment for WDM multicast network to cover the maximum number of destinations for minimizing the network cost. The computational complexity of the problem was also studied. Three heuristic algorithms were proposed and the worst-case approximation ratios for some heuristic algorithms were given. They also derive a lower bound of the minimum total wavelength cost and an upper bound of the maximum number of reached destinations. The efficiency of the proposed heuristic algorithms and the effectiveness of the derived bounds were verified by the simulation results.

S. J. B. Yoo [80], reviewed various wavelength conversion techniques, discusses the advantages and shortcomings of each technique and addressed their implications for transparent networks.

2.3. Routing Schemes for Survivable Networks

In this section, a comprehensive literature review of various routing schemes for optical networks has been described.

Ahmed Mokhtar *et. al.* [22], proposed the adaptive routing algorithms to improve the blocking performance of the network. They considered routing and wavelength assignment in wavelength-routed all-optical networks with circuit switching. They adopted a general approach in which they considered all paths between a source–destination (s–d) pair and incorporate network state information into the routing decision. This approach performs routing and wavelength assignment jointly and adaptively and outperforms fixed routing techniques. They also presented adaptive routing and wavelength assignment algorithms and evaluated their blocking performance. They have also obtained an analytical technique to compute approximate blocking probabilities for networks employing fixed and alternate routing.

Yoo Younghwan *et. al.* [23], presented four adaptive routing algorithms which favour paths with near-maximum number of available wavelengths between two nodes, resulting in improved load balancing. These presented adaptive routing algorithms were simulated and compared with least loaded and fixed routing algorithms for small networks. First-fit wavelength assignment policy was used for simulation of these proposed algorithms.

G. Mohan *et. al.* [24], considered wavelength rerouting in wavelength routed wavelength division multiplexed networks with circuit switching. The lightpaths between source–destination pairs were dynamically established and released in response to a random pattern of connection arrival requests and connection holding times. They also presented a time optimal rerouting algorithm for wavelength-routed WDM networks with parallel Move-to-Vacant Wavelength-Retuning (MTV-WR) rerouting scheme.

R. Ramaswami *et. al.* [27], considered the problem of routing connections in a reconfigurable optical network using wavelength division multiplexing. They derived an upper bound on carried traffic of connections for any routing and wavelength assignment algorithm in a network.

R. Ramamurthy *et. al.* [29], proposed an approximate analytical model that incorporates alternate routing and sparse wavelength conversion. They considered an optical network which employed wavelength routing cross-connects that enabled the establishment of wavelength-division-multiplexed connections between the node pairs. The simulations studied the relationships between alternate routing and wavelength conversion which were performed on three representative network topologies.

Xiaowen Chu *et. al.* [40], considered rerouting as an effective approach to decrease the blocking probability in legacy circuit-switched networks and proposed a routing algorithm. They also implemented intentional lightpath rerouting in all-optical WDM mesh networks. They proposed a Dynamic Least Congested Routing (DLCR) algorithm which dynamically switches the lightpath between the primary route and alternate route according to the network traffic distribution. Extensive simulation results showed that DLCR algorithm achieved better blocking performance than traditional routing algorithms including shortest path routing, fixed-alternate routing and least congested path routing.

Wang Yao *et. al.* [41], studied the rerouting approach and proposed different rerouting schemes for the provisioning of multi-granularity connections in two-layer wavelength-routed optical networks with grooming capability. They considered the dynamic traffic environment where connection requests arrive and depart dynamically. The rerouting procedure was applied only when the normal routing fail. They employed rerouting approach to improve the network throughput under the dynamic traffic model. They proposed two rerouting schemes, Rerouting at Lightpath Level (RRAL) and Rerouting at Connection Level (RRAC). A qualitative comparison was made between RRAL and RRAC. They have also proposed the critical-wavelength-avoiding one-lightpath-limited (CWA-1L) and Critical-Lightpath-Avoiding One-Connection-limited (CLA-1C) rerouting heuristics, which were based on the two rerouting schemes respectively. Simulation results showed that blocking probability was significantly reduced by these rerouting schemes.

Hiroaki Harai *et. al.* [43], studied routing methods and proposed a dynamic routing algorithm in all-optical switching networks. In all-optical switching networks the connections with more hops encounters more call blocking and it is especially true in optical networks with no wavelength conversions. An alternate routing method was considered with limited trunk reservation. Through developing an approximate analytical approach they showed that their method keeps good performance when compared with the existing alternate routing methods. The fairness among connections was also improved. Further, performance improvement was investigated by introducing a wavelength assignment policy and a dynamic routing method. An effectiveness of the proposed methods was investigated through simulation.

Anwar Alyatama [58], used fixed routing schemes and presented an approximate analytical method to evaluate the blocking probabilities in wavelength division multiplexing networks without wavelength converters. The approach assumed fixed routing with random or first-fit wavelength assignment.

Lei Guo *et. al.* [81], proposed two heuristics based on the principle of rerouting optimization. They focused on studying the problem of survivable routing provisioning to prevent single link failure in wavelength division multiplexed mesh network and proposed a fast online heuristic based on Mixed Shared Path Protection (MSPP) to provide the survivable routing for each connection request.

Xiaowen Chu *et. al.* [82], studied lightpath rerouting in optical WDM networks and investigated two rerouting strategies: passive rerouting and intentional rerouting. They concluded, for full wavelength convertible network rerouting can take place with the help of path-adjustment and for wavelength non-convertible networks wavelength retuning can be used to improve the blocking performance. In all the topologies they investigated, passive rerouting outperformed intentional rerouting a lot. According to them, intentional rerouting can also improve the blocking performance but not as notable as wavelength-retuning.

Kuo-Chun Lee *et. al.* [83], proposed different rerouting algorithms and minimized of incurred disruption due to rerouting in a wide-area all optical WDM network with random circuit arrivals and departures. Wavelength rerouting has been proposed to rearrange certain existing circuits to create a wavelength-continuous route in order to accommodate a new circuit. To reduce the disruption period, MTV-WR was used as the basic operation of circuit migration in which a circuit was moved to a vacant wavelength on the same path and parallel MTV-WR rerouting was used to reroute multiple circuits. An optimal algorithm was developed to minimize the weighted number of rerouted circuits with parallel MTV-WR rerouting. An algorithm was also developed to minimize the number of Branch-and-Exchange (BE) operations for the network to reconfigure the current topology to the target topology. To minimize the incurred disruption in wavelength rerouting, they have designed a new circuit migration scheme for rerouting circuits to greatly reduce the disruption period. An algorithm to select the fewest number of circuits to be rerouted was also designed. In this paper, they employed rerouting to improve call blocking probability due to the wavelength continuity constraint in circuit-switched wavelength-division-multiplexed all-optical networks.

Mohamed Koubaa *et. al.* [84], considered two traffic classes and they proposed a new lightpath rerouting algorithm which minimized the amount of rerouted WDM channels. SLD rerouting is forbidden while the establishment of a new Random Lightpath Demand (RLD) may require the rerouting of one or several RLDs. Simulation results showed that proposed algorithm improved the rejection ratio and consumes less CPU time than earlier presented rerouting algorithms.

Quang-Dzung Ho *et. al.* [85], proposed a novel rerouting approach which actively packs existing connections of different bandwidth granularities. Their algorithm estimates the potential resource gains of each existing connection and then reroutes only a small number of candidate connections that may give the largest gains. Therefore, it can efficiently reduce the rerouting costs, i.e., the required overheads and computations while maximizing the amount of resources that can be conserved for future requests. Simulation results showed that this approach kept the rerouting costs at a low level but it can significantly improve the blocking performance of the network.

Elias A. Doumith *et. al.* [86], considered DLE as a mixture of pre-planned traffic and random traffic. They proposed a routing scheme based on the reservation of network resources during a period Δ. An appropriate choice of Δ yields the performance results close to those which should have been obtained with the knowledge of connections duration. Two approaches for the acceptance of random traffic demands were compared.

Hongsik Choi *et. al.* [87], presented a link failure routing algorithm which pre-computed backup paths for links in order to tolerate double link failure. They motivated the need for considering double-link failures and presented three loop back methods for handling such failures. In the first two methods, two edge-disjoint backup paths were computed on each link for rerouting traffic on the failure of a link for s-d pair. These methods required the identification of the failed links before recovery. The third method requires the pre-computation of a single backup path and did not require link identification before recovery.

Krishanth mohan *et. al.* [88], proposed two rerouting schemes and addressed the problem of dynamic routing of sub-lambda connections with differentiated survivability using multi-layer protection and inter-layer backup resource sharing in IP/MPLS-over-WDM networks. They proposed two rerouting-based dynamic routing schemes for reduction of the blocking of mission-critical connections. In these schemes, rerouting operation was done with the use of lightpaths called potential lightpaths and an efficient heuristic algorithm was proposed for choosing them.

Alexander Birman [89], studied wavelength routing schemes for a class of all-optical networks using wavelength division multiplexing. Using a generalized reduced load approximation scheme, he calculated the blocking probabilities for the optical network model for two routing schemes: fixed routing and least loaded routing.

Krishna Bala *et. al.* [90], proposed routing algorithms for setting up calls on a circuit-switched basis in Linear Lightwave Networks (LLN). The overall problem was decomposed into three sub-problems: (1) Physical path allocation (2) Checking for violations of the special optical constraints on the allocated physical path and

(3) Channel assignment. Only point to point connections were considered for these routing algorithms.

S. Dharma Rao *et. al.* [91], proposed distributed dynamic routing algorithms for QoS constrained routing and survivable routing based on preferred link routing approach. For QoS constrained routing they provided a common framework for routing connections with constraints on different types of metrics such as bandwidth, delay, bit-error-rate and reliability. A distributed routing algorithm for fault-tolerant connections was also proposed and described how dedicated and shared protection can be provided in case of single link failures and studied the performance of fault-tolerant routing in terms of call acceptance ratio, cost of the path, hop length, call setup time and compared the results with that of an existing approach.

Yabin Ye *et. al.* [92], proposed an algorithm named max-spare algorithm for locating regeneration nodes for a lightpath. This algorithm was then compared with a greedy algorithm in conjunction with two routing algorithms namely, Wavelength Weighted (WW) and Length Weighted (LW) routing algorithms.

Jan Spath [93], concentrated on the dynamic routing in WDM networks. It was shown that a strategy based on pre-calculated alternatives and an adaptive dynamic path search performs very well over a wide range of load. Moreover, specific affects for the impact of resource allocation strategies in photonic WDM networks were highlighted, especially the influence of wavelength converter usage strategies in networks with partial conversion. Also he investigated the way non-Poisson traffic behaviour affects performance of routing strategies. He also presented how the results from dynamic routing investigation can help in optimization of the network planning process.

Yu Dong *et. al.* [94], presented a failure aware routing algorithm and enhanced fault tolerance in large-scale optical switches through innovations in architecture and control logic design. A large-scale switch is constructed from a network of 2 × 2 optical Switch Elements (SEs). There were three major contributions: (1) they developed an analytical method to calculate the average connection blocking probability in a faulty switch network referred to as the probability accumulation method; (2) they provided a failure-aware routing algorithm to effectively circumvent connections from defected SEs in a dilated Benes switch and (3) they improved the connectivity pattern of the Benes network to further reduce the blocking probability, especially when the SE failure rate is low.

2.4. Grooming and RWA problem

In this section, detailed literature survey related to RWA problem for WDM optical network has been presented.

James Yiming Zhang *et. al.* [95], studied RWA problem in a semi-dynamic scenario where rearrangements were conducted in a series of sessions after variation in traffic demands. Unlike pure static RWA problems each rearrangement scheme must consider established lightpaths in the previous session. A novel formulation of the WDM network rearrangement problem was used to minimize rejected demands and rerouted lightpaths. This was done by coordinating the re-routing of existing lightpaths with the adaptation to varying demands.

Sungwoo Tak *et. al.* [96], developed three algorithms for restorable routing and wavelength assignment. They also evaluated existing restoration models and their performance in an attempt to verify their performance and efficacy. They proposed a restoration framework and examined its performance. The proposed restoration framework constituted of seven objective functions and three algorithms. Seven objective functions yield their own objective goals significant to the optimal design of a survivable WDM optical network. Three algorithms were exploited to measure the performance of the objective functions. They were Deep Conjectural Reinforced local Optimal Search (DCROS), Hybrid Restoration Method (HRM) and Random Walk-based Wavelength Assignment (RWWA) algorithms. These algorithms were used to find a set of disjoint lightpaths for a given objective function. Each of those disjoint lightpaths was used for a primary lightpath and a backup lightpath.

Paramjeet Singh *et. al.* [97], considered the routing and wavelength assignment problem on wavelength division multiplexing networks without wavelength conversion. They have proposed three dynamic link weight assignment strategies that change the link weight according to the traffic. The performance of the existing trend and the proposed strategies was shown in terms of blocking probability. The simulation results showed that all the proposed strategies perform better than the existing trend.

Tongyu Song *et. al.* [98], proposed a simulation algorithm to re-evaluate the different RWA algorithms with an emphases on their robustness to the accumulation of homodyne cross-talks. The performance of six RWA algorithms was compared in a novel perspective i.e. their potential to reduce the number of lightpaths with unacceptable signal quality.

Yabin Ye *et. al.* [99], studied RWA algorithms whose optimum object was the minimization of the number of wavelength required in wavelength division multiplexing all optical network. A statistics method was also proposed to modify the RWA algorithms and this method was used to compare the performance of different RWA algorithms.

Xiaoping Zheng *et. al.* [100], studied dynamic RWA algorithms for WDM networks and proposed Multi-Granularity Optical Cross-Connect (MG-OXC) to reduce the complexity and size of optical switch. They presented an online adaptive routing algorithm to solve this problem. Simulation results showed that for a two-stage multi-granularity optical network the blocking probability can be greatly affected by the fiber-tunnel topology. For the further improvement of the network performance a fiber-tunnel topology optimization algorithm was proposed and simulation results showed that the blocking probability could be drastically reduced after fiber-tunnel topology reconfiguration.

Harsha V. Madhyastha *et. al.* [101], addressed the problem of routing and wavelength assignment of multicast sessions with sub-wavelength traffic demands in the scenario of metropolitan WDM ring networks. They considered two different node architectures which perform duplication in optical and electronic domain respectively. They studied the problem of assigning routes and wavelengths to the multicast sessions so as to minimize electronic copying. Also, an ILP formulation was presented for this problem and a heuristic algorithm was proposed which implemented the routing as well as circle construction phases simultaneously and then groups the circles.

Motivated by the increasing importance of multi-fiber WDM networks, Christos Nomikos *et. al.* [102], studied a routing and wavelength assignment problem in a networks. In this problem the number of wavelengths per fiber was given and the goal was to minimize the cost of fiber links that was needed to be reserved in order to satisfy a set of communication requests. They introduced a generalized setting where network pricing was non-uniform, i.e. the cost of hiring a fiber may differ from link to link. Also, exact or constant-ratio approximation algorithms were presented for all variations in chain, ring and spider networks.

Harsha V. Madhyastha *et. al.* [103], suggested an effective algorithm for dynamic routing and wavelength assignment algorithm for sub-wavelength connections. Also, they also addressed the issue of traffic grooming in arbitrary WDM mesh networks and presented a novel groomer architecture wherein a combination of grooming at two different granularities was utilized to make the setup cost-effective without compromising on efficiency. Also, a means of rerouting connections dynamically was proposed to facilitate the increase in average call acceptance ratio.

Maher Ali *et. al.* [104], investigated the RWA problem for degradation of routed signals by optical components. Previous studies have solved many variations of the RWA problem in optical networks under the assumption of perfect conditions regarding the power of a signal. The problem was formulated as a mixed-integer non-linear program. They proposed a two-phase approach; in the first phase, they solved the pure RWA problem using fixed routes for every connection and in the second phase, power assignment was accomplished by either using a heuristic or by using a genetic algorithm.

B. Jaumarda *et. al.* [105], presented a review of the ILP formulations that have been proposed for the routing and wavelength assignment problem in WDM optical networks assuming asymmetrical traffic. They showed that all formulations proposed under asymmetrical traffic assumptions both link and path formulations were equivalent in terms of the upper bound value provided by the optimal solution of their linear programming relaxation, although there was a wide difference in the number of variables and constraints. They have proposed improvements for some of the formulations that resulted in further reduction in the number of variables and constraints.

With the rapid development of optical networking technology, it was a realizable technique to support point-to-multi point connections directly on the optical layer giving rise to optical multicast. The topic of optical multicast has attracted much enthusiasm for the reason that it was used not only to make full use of the abundant bandwidth provided by optical fibers but also to take full advantage of multicast over the traditional point-to-point connection approach. Yinzhu Zhou *et. al.* [106], presented a comprehensive review of optical multicast over wavelength-routed WDM networks covering the development of both data plane and control plane designs. They have provided an up-to-date state-of-the-art review on the multicast routing and wavelength assignment problem.

Li-Wei Chen *et. al.* [107], considered routing and wavelength assignment in ring, torus and tree topologies with the twin objectives of minimizing wavelength usage and maximizing optical bypass. Also, RWA and bypass algorithms were developed for both tori and trees by embedding virtual rings within these topologies.

Paramjeet Singh *et. al.* [108], considered RWA problem on wavelength division multiplexing networks without wavelength conversion. Also, they presented efficient RWA strategies which were used to minimize the blocking probability.

Osama Awwad *et. al.* [109], considered the RWA problem with traffic grooming for mesh networks under static and dynamic lightpath connection requests. They proposed an Integer Linear Programming (ILP) model that accurately depicted the Grooming Routing and Wavelength Assignment problem (GRWA). The problem of grooming routing and wavelength assignment was solved by proposing two novel heuristics. The strength of these proposed heuristics stems from their simplicity, efficiency and applicability to large-scale networks.

Ming-Tsung Chena *et. al.* [110], studied and extended Multicast Routing and Wavelength Assignment (MRWA) problem with Delay Constraint (MRWA-DC) that incorporated delay constraints in WDM networks having heterogeneous light splitting capabilities. Their objective was minimization of multicast cost of the light-forest. An integer linear programming model was also proposed to formulate and solve that problem. To solve the problem in large-scale networks Near-K-Shortest-Path Heuristic (NKSPH), was also developed. Numerical results indicated that the proposed heuristic algorithm produced approximate solutions of good quality in an acceptable time.

CHAPTER III

MODELS FOR BLOCKING PROBABILITY

Publications from chapter

1. Amit Wason, R.S. Kaler, “Blocking in wavelength-routed all-optical WDM networks,” *Optik– International Journal for Light and Electron Optics- Elsevier Science*, vol. 121, no. 10, pp. 903-907, June 2010.
2. Amit Wason, R. S. Kaler, “Blocking in wavelength–routed all-optical WDM network with or without wavelength conversion,” *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 121, no. 23, pp. 2162-2165, December 2010.
3. Amit Wason, R. S. Kaler, “Blocking in wavelength–routed all-optical WDM network with wavelength conversion,” *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 7, pp. 631-634, April 2011.
4. Amit Wason, R. S. Kaler, “Blocking Probability Calculation in Wavelength–Routed All–Optical Networks,” *Optik -International Journal for Light and Electron Optics-Elsevier Science* In Press, Corrected Proof, Available online 21 January 2011.

The blocking probability of a lightpath request (or a call) is an important performance measure of a wavelength-routed network. This blocking probability can be affected by many factors such as network topology, traffic load, number of links, algorithms employed and whether wavelength conversion is available or not. This Chapter focuses on low complexity mathematical model for calculation and reduction of blocking probability of WDM optical network for both wavelength convertible as well as non-convertible networks which is related to all objectives of the research work. These mathematical models proposed have closed-form expression and do not require much simulation statistics. They have low implementation complexity and the computation used is quite efficient. These models suggest the best optimum path and appropriate number of free wavelengths in the given network. We can go for the compromise between path length and the number of free wavelength. These models are used to evaluate and improve the blocking performance of any network topology (such as NSFnet).

3.1. Blocking in Wavelength Routed All-Optical Networks

Many analytical models have been proposed in the literature but some of them are very complex and lots of simulation statistics are required to evaluate the performance of the system by using these models. The models proposed in literature are such that the mathematical computations used are very complicated. Further, computation time of these models is also quite large. So, there was a requirement of such mathematical models which use low complexity and computation should also be very efficient. In this chapter, we have developed low complexity mathematical models which do not require any simulation statistics. These models have low implementation complexity and computation is also quite efficient. These models suggest an optimum path as a solution to RWA problem.

3.2. Proposed Mathematical Model for WDM Optical Networks

We have proposed different Mathematical models for WDM optical Networks which can be used for wavelength convertible networks as well as wavelength non-convertible networks. We have denoted the path and the network-wide parameters by upper-case letters and link parameters by lower case letters. Subscripts and superscripts refer to specific instances of links, node pairs and routes.

- N is the number of nodes in WDM network; $N \in V$.
- l is the length of route or the number of links in the route or path selected.
- r is the number of routes available where $r \in R$.
- P_B^r is the blocking probability of r routes.
- P_B is the overall blocking probability of the network.
- P_{BW}^r is the blocking probability caused by insufficient wavelength.
- P_{BC}^r is the blocking probability caused by lack of converter.
- L is the load applied on the route.
- $N\lambda$ is the number of free wavelengths.

We have assumed the network without wavelength conversion. Given N node WDM network, all nodes forms a set V and all directed links are contained in as set E. Suppose fixed path routing policy is adopted for lightpath establishment the predetermined directed routes are indicated with a set R.

3.2.1 Mathematical Models for Wavelength Non–Convertible WDM Networks

For each route $r \in R$, blocking probability for connections along route r can be divided into two mutual exclusive parts; P_{BW}^{r} and P_{BC}^{r}. The total blocking probability for a network depends upon the two parameters; blocking probability of the system due to the lack of wavelengths and blocking probability of the system due to the lack of converters. Thus we can have the total blocking probability of the system as the sum of blocking probability due to lack of wavelength and blocking probability due to lack of converters. Thus, the total blocking probability of the network with wavelength conversion as given in [2] is given as:

$$P_{B}^{r} = P_{BW}^{r} + P_{BC}^{r} \ \forall\, r \in R \tag{3.1}$$

According to [111], the average blocking probability in the network is given by:

$$P_{B} = \frac{\sum_{r \in R} L^{r} P_{B}^{r}}{\sum_{r \in R} L^{r}} \tag{3.2}$$

$$P_{B} = \frac{\sum_{r \in R} L^{r} P_{BW}^{r}}{\sum_{r \in R} L^{r}} + \frac{\sum_{r \in R} L^{r} P_{BC}^{r}}{\sum_{r \in R} L^{r}} \tag{3.3}$$

For a network without wavelength conversion the value of blocking probability of the system due to lack of converters will be zero i.e. $P_{BC}^{r} = 0$. Thus, total blocking probability for a network without wavelength conversion is given by:

$$P_{B}^{r} = P_{BW}^{r} \tag{3.4}$$

$$P_{B} = \frac{\sum_{r \in R} L^{r} P_{BW}^{r}}{\sum_{r \in R} L^{r}} \tag{3.5}$$

Also, Load L for a network with given free wavelengths $N\lambda$ and the length of route l is given by:

$$L = \frac{N\lambda}{l} \tag{3.6}$$

Hence, total blocking probability for the network without wavelength conversion is given by:

$$P_B = \frac{\sum_{r\in R}\left(\frac{N\lambda}{l}\right)^r P_{BW}^r}{\sum_{r\in R}\left(\frac{N\lambda}{l}\right)^r} \tag{3.7}$$

The equation (3.7) describes proposed mathematical model (*Model-I*) for calculation of blocking probability of wavelength convertible network.

From equation (3.1) and equation (3.2), we can reduce the value of P_B as:

$$P_B = \frac{\sum_{r\in R} L^r P_{BW}^r}{\sum_{r\in R} L^r} + \frac{\sum_{r\in R} L^r P_{BC}^r}{\sum_{r\in R} L^r} \tag{3.8}$$

But P_{BW}^r and P_{BC}^r can be given by equation (3.9) and equation (3.10) as:

$$P_{BW}^r = \frac{\frac{1}{W!}}{\sum_{i=0}^{W}\frac{(L)^i}{i!}} \tag{3.9}$$

$$P_{BC}^r = \frac{\frac{1}{C!}}{\sum_{i=0}^{C}\frac{(L)^i}{i!}} \tag{3.10}$$

Further, we can substitute the value of P_{BW}^r and P_{BC}^r from equation (3.9) and equation (3.10) to equation (3.8) and the value of the blocking probability P_B can be given as in [112] by equation (3.11):

$$P_B = \frac{\sum_{r\epsilon R}(L)^{r+1}\left[\frac{\frac{1}{W!}}{\sum_{i=0}^{W}\frac{(L)^i}{i!}} + \frac{\frac{1}{C!}}{\sum_{i=0}^{C}\frac{(L)^i}{i!}}\right]}{\sum_{r\epsilon R}(L)^r} \tag{3.11}$$

Equation (3.11) can further be reduced to equation (3.12) as:

$$P_B = \frac{\sum_{r\epsilon R}\left(\frac{N\lambda}{l}\right)^{r+1}\left[\frac{\frac{1}{W!}}{\sum_{i=0}^{W}\frac{\left(\frac{N\lambda}{l}\right)^i}{i!}} + \frac{\frac{1}{C!}}{\sum_{i=0}^{C}\frac{\left(\frac{N\lambda}{l}\right)^i}{i!}}\right]}{\sum_{r\epsilon R}\left(\frac{N\lambda}{l}\right)^r} \tag{3.12}$$

The equation (3.12) describes proposed mathematical model (*Model-II*) for calculation of blocking probability of the wavelength convertible network.

3.2.2 Mathematical Model for Wavelength Convertible WDM Networks

For each route $r \in R$, blocking probability for connections along route r can be divided into two mutual exclusive parts; P_{BW}^{r} and P_{BC}^{r}. The total blocking probability for a network depends upon the two parameters; blocking probability of the system due to lack of wavelengths and blocking probability of the system due to lack of converters. Thus we can have the total blocking probability of the system as the sum of blocking probability due to lack of wavelength and blocking probability due to lack of converters. Thus, the total blocking probability of the network with wavelength conversion as given in [2] is given as:

$$P_B^r = P_{BW}^r + P_{BC}^r, \ \ r \in R \tag{3.13}$$

We can have the value of overall blocking probability P_B as given in [113] as:

$$P_B = \left[\frac{\sum_{r\in R} L^r P_B^r}{\sum_{r\in R} L^r}\right] - P_N \tag{3.14}$$

$$P_B = \left[\frac{\sum_{r\in R} L^r P_{BW}^r}{\sum_{r\in R} L^r} + \frac{\sum_{r\in R} L^r P_{BC}^r}{\sum_{r\in R} L^r}\right] - P_N \tag{3.15}$$

$$P_B = \left[\frac{\sum_{r\epsilon R} (L)^{r+1} \left[\frac{\frac{1}{W!}}{\sum_{i=0}^{W} \frac{(L)^i}{i!}} + \frac{\frac{1}{C!}}{\sum_{i=0}^{C} \frac{(L)^i}{i!}}\right]}{\sum_{r\epsilon R} (L)^r}\right] - P_N \tag{3.16}$$

Where P_N represents probability of system when first blocking occurs, which can be given by *Poisson formula* and a wavelength is converted to other fixed wavelength and its value can be calculated as in equation (3.17).

$$P_N = \frac{Total\ number\ of\ calls\ blocked}{Total\ number\ of\ calls\ generated} \tag{3.17}$$

The equation (3.16) describes the proposed mathematical model (*Model-III*) for the calculation of blocking probability of wavelength convertible network.

3.2.3 Mathematical Model for both Wavelength Convertible and Non-Convertible WDM Networks

- *Notations used:*

We have used following notations:

- s and d denotes source and destination of an end-to-end traffic request. The end-to-end traffic may traverse through a single lightpath or multiple lightpath.
- N: Number of nodes in WDM network.
- l: Number of links in route or path selected and all links have C channels.
- r: Number of routes available where $r \in R$.
- $B(C, L_{sd}^r)$: Erlang loss formula for L_{sd}^r load and C channels.
- B_{sd}: Blocking probability; B_{sd}= 0 if the request from node s to node d has been successfully routed; otherwise, B_{sd}=1, call blocked.
- B_{sd}^r: Blocking probability of r routes
- L_{sd}^r: Load of the route r.

Given

- N node WDM network
- All nodes form a set V.
- E is the set of all directed links.
- Fixed path routing policy is adopted for the establishment of lightpath.
- R indicates the set of predetermined directed routes.

As given by A. Birman in [89], for each route $r \in R$, the blocking probability for connections along route r can be given by equation (3.18).

$$B_{sd} = 1 - [1 - B(C, L_{sd}^r)]^l \tag{3.18}$$

Where $B(C, L_{sd}^r)$ is represented by Erlang's loss formula and is given by eq. (3.19) as:

$$B(C, L_{sd}^r) = \frac{\frac{(L_{sd}^r)^C}{C!}}{\sum_{i=0}^{C} \frac{(L_{sd}^r)^i}{i!}} \tag{3.19}$$

Substituting the value of Erlang's loss formula in equation (3.18) from equation (3.19) we get the value of blocking probability as

$$B_{sd} = 1 - \left[1 - \frac{\frac{(L_{sd}^r)^C}{C!}}{\sum_{i=0}^{C} \frac{(L_{sd}^r)^i}{i!}} \right]^l \tag{3.20}$$

$$B_{sd} = 1 - \left[1 - \frac{\frac{\left(\frac{N\lambda}{l}\right)^C}{C!}}{\sum_{i=0}^{C} \frac{\left(\frac{N\lambda}{l}\right)^i}{i!}} \right]^l \tag{3.21}$$

The equation (3.21) describes the proposed mathematical model (*Model-IV*) for calculation of blocking probability for both wavelength convertible and wavelength non-convertible WDM Networks.

3.3. Results and Discussions

We can use the proposed model for the calculation of blocking probability of WDM optical networks. These mathematical models have been implemented on realistic networks such as NSFnet network topology.

3.3.1. Wavelength Non–Convertible WDM Optical Networks

We have proposed two different models for Wavelength non-convertible WDM Optical Network.

3.3.1.1 Model-I

We have considered the network without wavelength conversion. The total blocking probability of the network depends on P_{BW}^r, i.e. blocking probability caused by insufficient wavelength. This blocking probability can be reduced and fixed to a particular level and hence the probability of a network depends only on number of free wavelengths and length of the route. We have fixed the value of blocking probability of free wavelength to 0.1, varied the number of free wavelengths and length of route and calculated total blocking probability of given network.

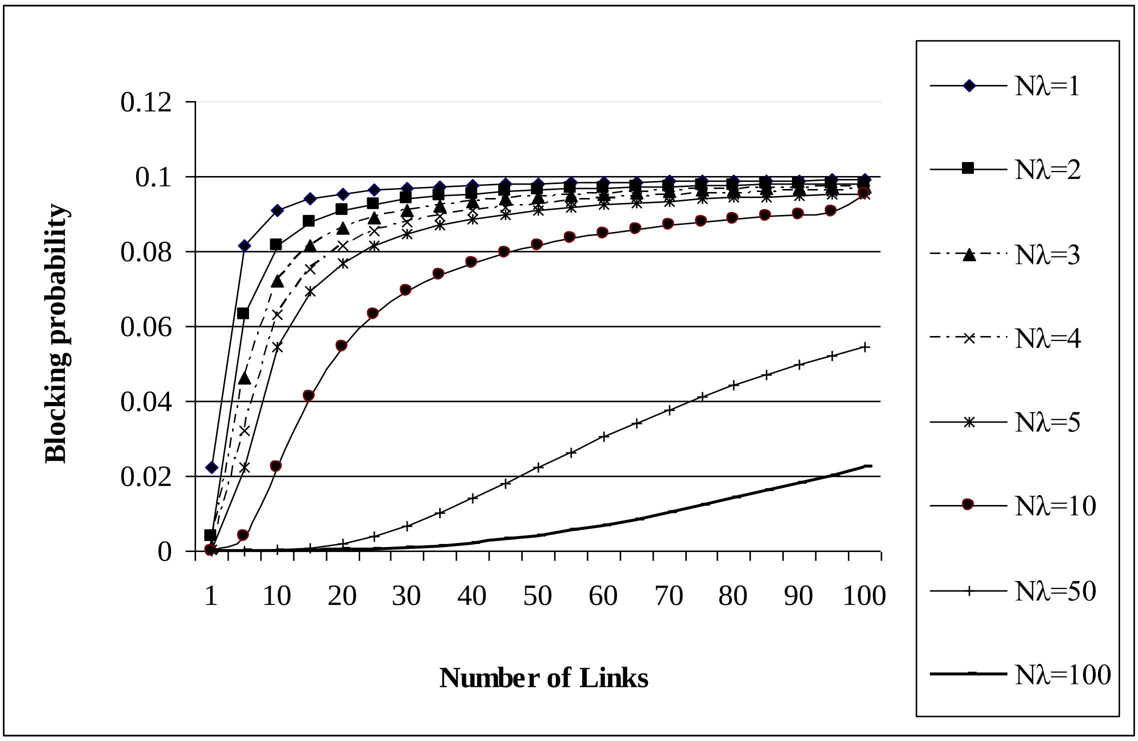


Figure 3.1: Blocking probability vs. No. of Links (Model-I)

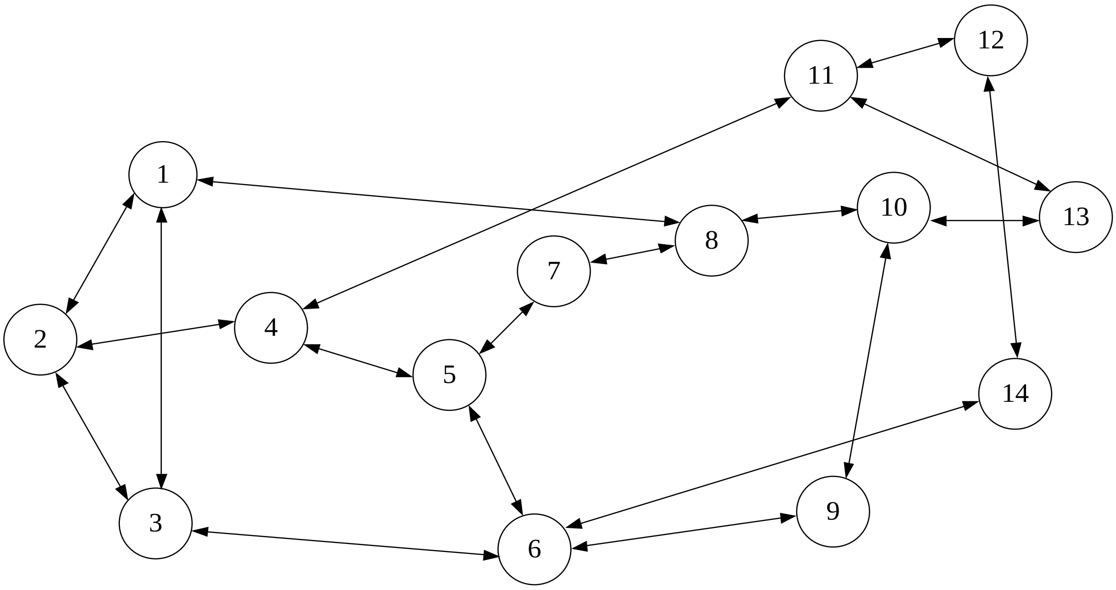


Figure 3.2: NSFnet network topology (14-nodes 19-links)

Table (3.1) shows the value of blocking probability of the network at a particular length of route l and have a number of free wavelengths $N\lambda$. It is clear from the table that blocking probability increases with increase in length of route and decreases with the increase in the number of free wavelengths present for that path. The simulation results have been shown in figure (3.1). The figure (3.1) shows that blocking probability can be minimized either by minimizing the number of links in selected route i.e. the shortest path route can be selected or by maximizing the number of free wavelengths. The model was applied to NSFnet network topology (14-nodes 19-links) which has been shown as in Figure (3.2). Figure (3.3) shows blocking probability variation with the number of free wavelengths for a given system. For NSFnet we have assumed 1 as source node

Table 3.1: Blocking probability for Model-I

Route Length	**Number of free Wavelengths**							
L	**Nλ=1**	**Nλ=2**	**Nλ=3**	**Nλ=4**	**Nλ=5**	**Nλ=10**	**Nλ=50**	**Nλ=100**
1	0.02222	0.00403	0.00118	0.00048	0.00025	4.50E-05	1.22E-05	1.10E-05
5	0.08169	0.06314	0.04614	0.03233	0.02222	0.004031	4.50E-05	1.84E-05
10	0.09091	0.08166	0.07234	0.06315	0.05433	0.022222	0.000248	4.50E-05
15	0.09396	0.08784	0.08166	0.07544	0.06925	0.041131	0.000849	0.000112
20	**0.09548**	0.09091	0.08630	0.08166	0.07700	0.054329	0.002067	0.000248
25	0.09638	0.09274	0.08907	0.08537	0.08166	0.063147	0.004031	0.000484
30	0.09699	0.09396	0.09091	0.08784	0.08476	0.06925	0.006744	0.000849
35	0.09742	0.09483	0.09222	0.08960	0.08696	0.07367	0.010101	0.00137
40	0.09774	**0.09548**	0.09320	0.09091	0.08861	0.076998	0.013925	0.002067
45	0.09799	0.09598	0.09396	0.09193	0.08989	0.079589	0.018024	0.002953
50	0.09820	0.09639	0.09457	0.09274	0.09091	0.081659	0.022222	0.004031
55	0.09836	0.09671	0.09506	0.09341	0.09174	0.08335	0.02638	0.005299
60	0.09850	0.09699	**0.09548**	0.09396	0.09244	0.084757	0.030398	0.006744
65	0.09861	0.09722	0.09583	0.09443	0.09302	0.085945	0.034215	0.008352
70	0.09871	0.09742	0.09613	0.09483	0.09352	0.086962	0.037797	0.010101
75	0.09880	0.09760	0.09639	0.09517	0.09396	0.087842	0.041131	0.011966
80	0.09887	0.09774	0.09661	**0.09548**	0.09434	0.08861	0.044217	0.013925
85	0.09894	0.09787	0.09681	0.09574	0.09467	0.089288	0.047065	0.015952
90	0.09900	0.09800	0.09699	0.09598	0.09497	0.089889	0.049688	0.018024
95	0.09905	0.09810	0.09715	0.09619	0.09524	0.090427	0.052104	0.02012
100	0.09909	0.09820	0.09729	0.09639	**0.09548**	**0.095477**	0.054329	0.022222

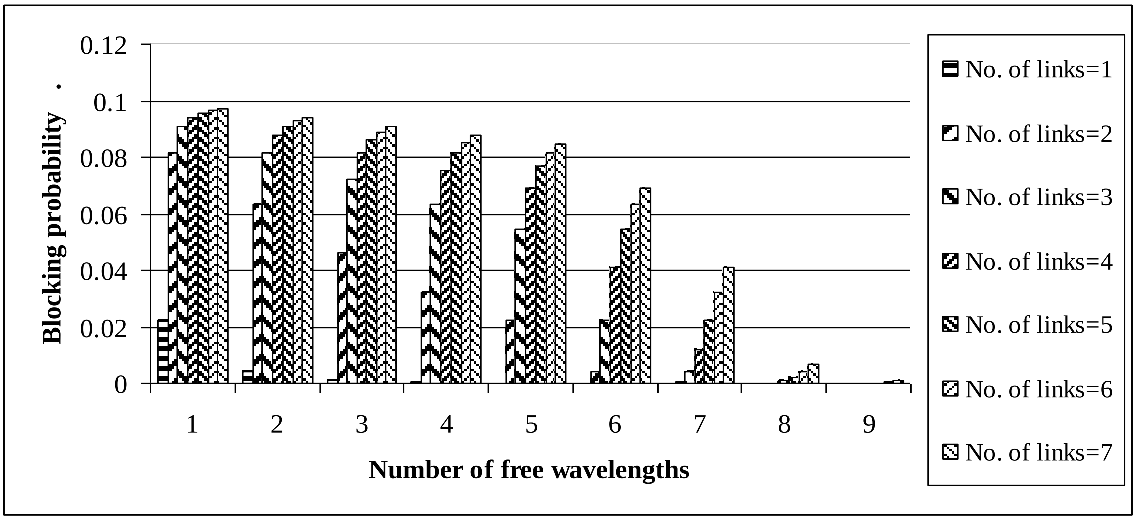


Figure 3.3: Blocking probability vs. Number of free wavelengths (Model-I)

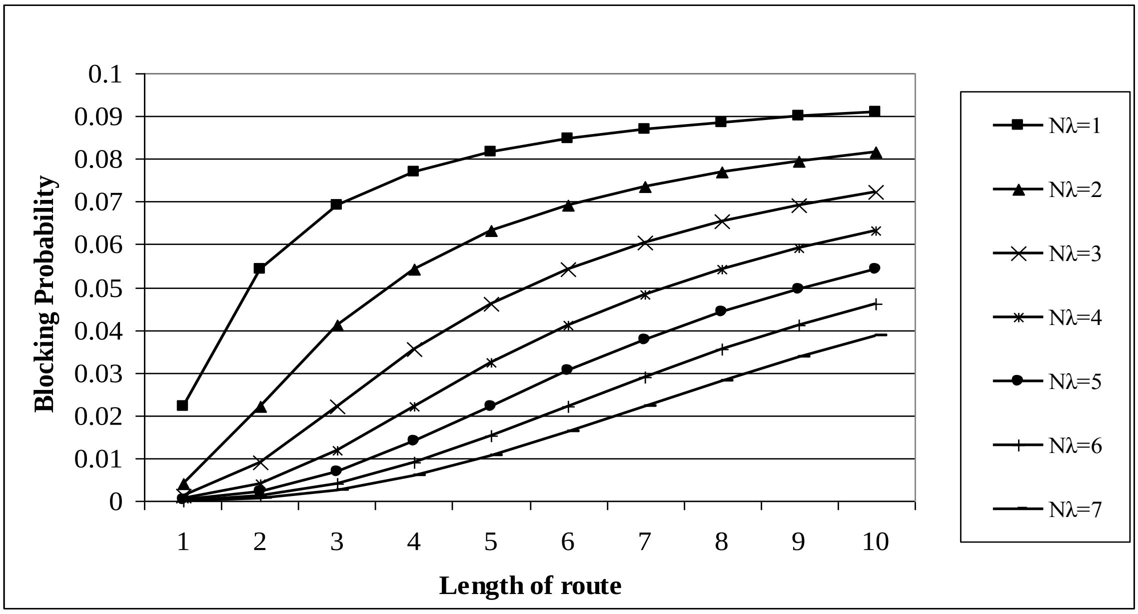


Figure 3.4: Blocking probability vs. Length of the route for NSFnet (Model-I)

and 14 as destination node. There are a number of routes from source to destination but the maximum length of route can be 10. The simulation results for the NSFnet using Model-I are shown in the figure (3.4) and figure (3.5).

It is clear from the figure (3.4), figure (3.5) and Table (3.2) that blocking probability is minimum with the Nλ=7 but we can achieve a compromise between route length and number of wavelengths by selecting the shortest path 1-3-6-14 i.e. with route length 4 and by selecting number of free wavelengths to 3 or 4. This model also suggests an optimum path as a solution to routing problem and hence we can reduce the blocking probability of the given network.

3.3.1.2 Model-II

We have considered the network with and without wavelength conversion. The total blocking probability of network depends on the $P_{BW}^{r}$and P_{BC}^{r}, i.e. the Blocking probability caused due to insufficient wavelength and blocking probability caused by lack of converter. The expression given in equation (3.12) shows that blocking probability depends on number of free wavelengths, total number of wavelengths available, number of links in the route or path selected, load on the route r and number of converters used in given network. The blocking probability of the network has been calculated according to this model for both wavelength convertible networks as well as for wavelength non-convertible networks. At first, we will discuss wavelength non-convertible networks. For network without wavelength conversion equation (3.12) is reduced to equation (3.22) and the blocking probability will be given by:

$$P_B = \frac{\sum_{r\epsilon R}\left(\frac{N\lambda}{l}\right)^{r+1}\left[\frac{\frac{1}{W!}}{\sum_{i=0}^{W}\frac{\left(\frac{N\lambda}{l}\right)^{i}}{i!}}\right]}{\sum_{r\epsilon R}\left(\frac{N\lambda}{l}\right)^{r}} \tag{3.22}$$

Figure (3.6) to figure (3.8) shows the blocking probability distribution with respect to the length of route or number of links for different range of route length. Figure (3.9) shows the distribution of blocking probability with respect to the maximum load (in Erlangs) per link. Model-II also suggests that blocking probability is decreasing with the increase in number of links for a particular number of free wavelengths. Figure (3.10) shows blocking probability distribution with respect to the route length for a wavelength convertible network. Table (3.3) shows the value of blocking probability of network at a particular length of route l (or number of links in selected route) for a number of free wavelengths. For Model-II, it is clear from table that blocking probability of network decreases with increase in the length of the route. It further decreases with increase in number of free wavelengths present for the path.

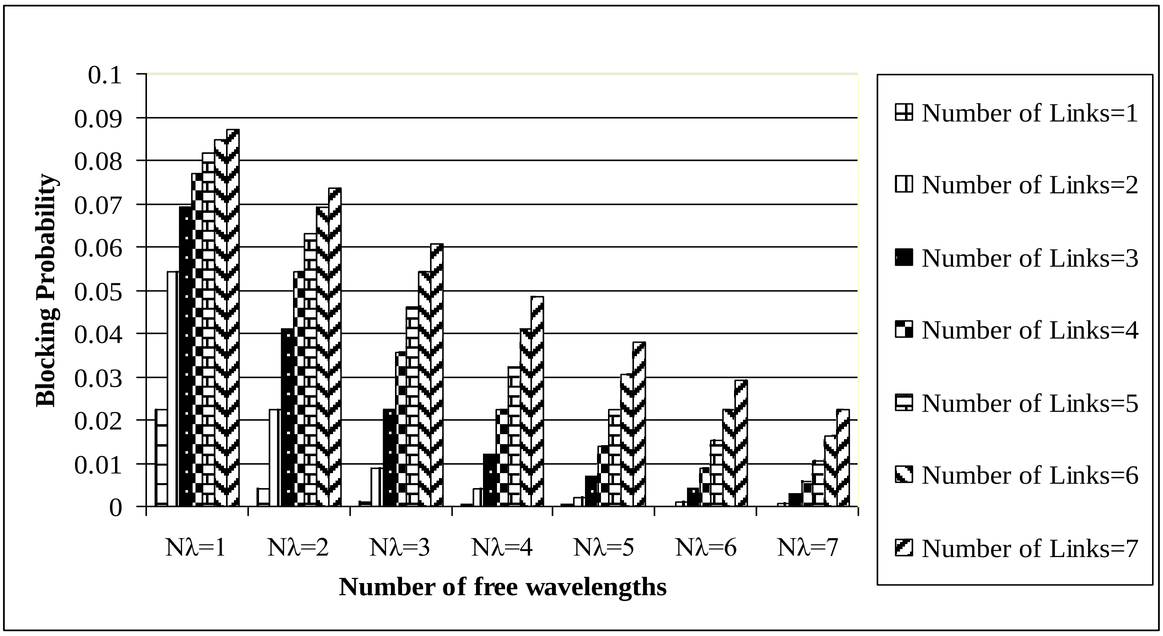


Figure 3.5: Blocking probability vs. Number of free wavelengths for NSFnet (Model-I)

Table 3.2: Blocking probability for NSFnet of Model-I

Route Length	**Number of free Wavelengths**						
L	**Nλ=1**	**Nλ=2**	**Nλ=3**	**Nλ=4**	**Nλ=5**	**Nλ=6**	**Nλ=7**
1	0.02222	0.004031	0.001178	0.000484	0.000248	0.000148	9.90E-05
2	0.05433	0.022222	0.00892	0.004031	0.002067	0.001178	0.00073
3	0.06925	0.041131	0.022222	0.011966	0.006744	0.004031	0.00255
4	0.07700	0.054329	0.035436	0.022222	0.013925	0.00892	0.005897
5	0.08166	0.063147	0.046141	0.032334	0.022222	0.01527	0.010623
6	0.08476	0.06925	0.054329	0.041131	0.030398	0.022222	0.016246
7	0.08696	0.07367	0.060577	0.048404	0.037797	0.029079	0.022222
8	0.08861	0.076998	0.06542	0.054329	0.044217	0.035436	0.028123
9	0.08989	0.079589	0.06925	0.059166	0.049688	0.041131	0.033684
10	0.09091	0.081659	0.072341	0.063147	0.054329	0.046141	0.038775

3.3.2. Wavelength Convertible WDM Optical Networks (Model-III)

We have considered given network as wavelength–routed all–optical WDM network with wavelength conversion. Total blocking probability of network depends upon P_{BW}^{r}

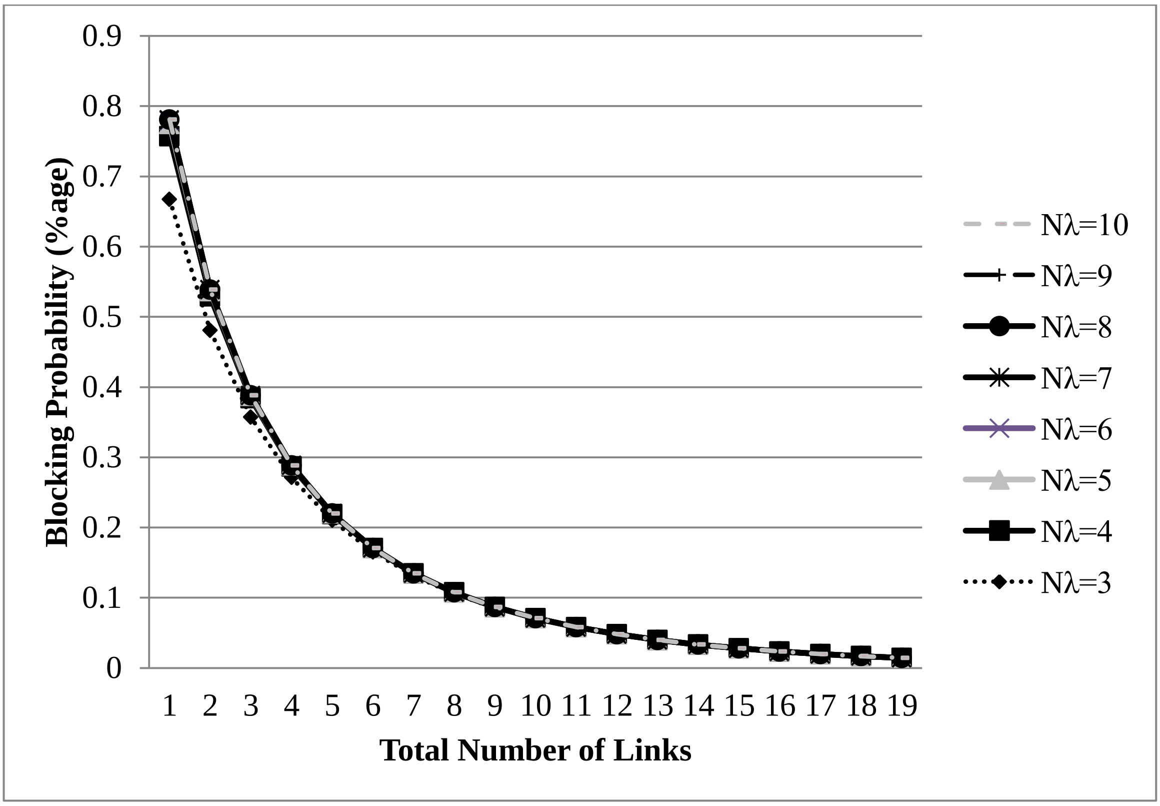


Figure 3.6: Blocking probability vs Number of Links (for no wavelength conversion) (Model-II)

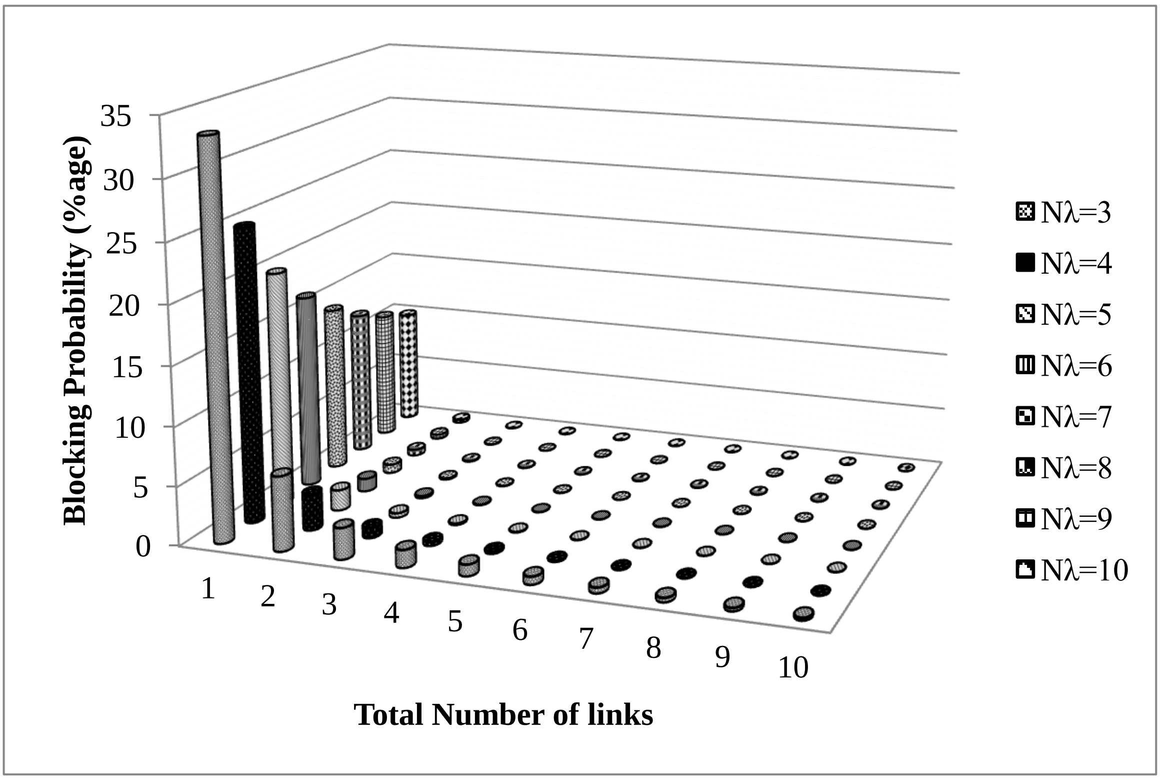


Figure 3.7: Blocking probability vs Number of Links for Model-II

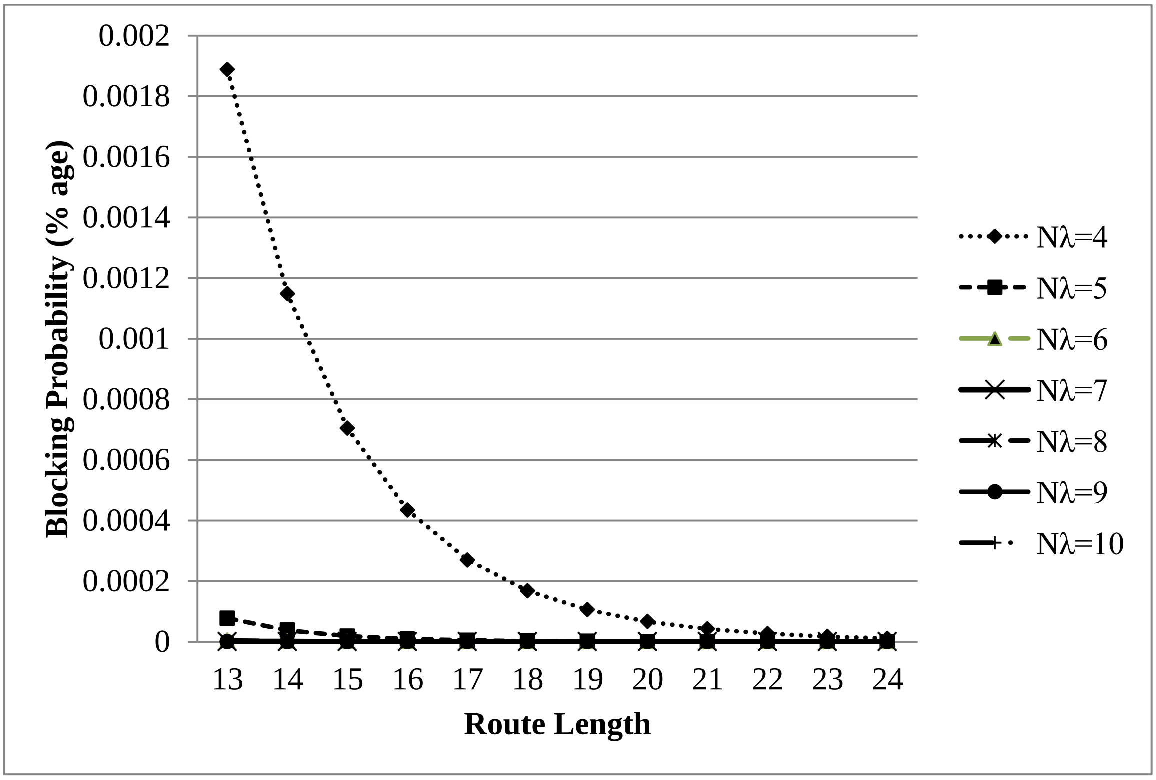


Figure 3.8: Blocking probability vs Route length for Model-II
(for no wavelength conversion)

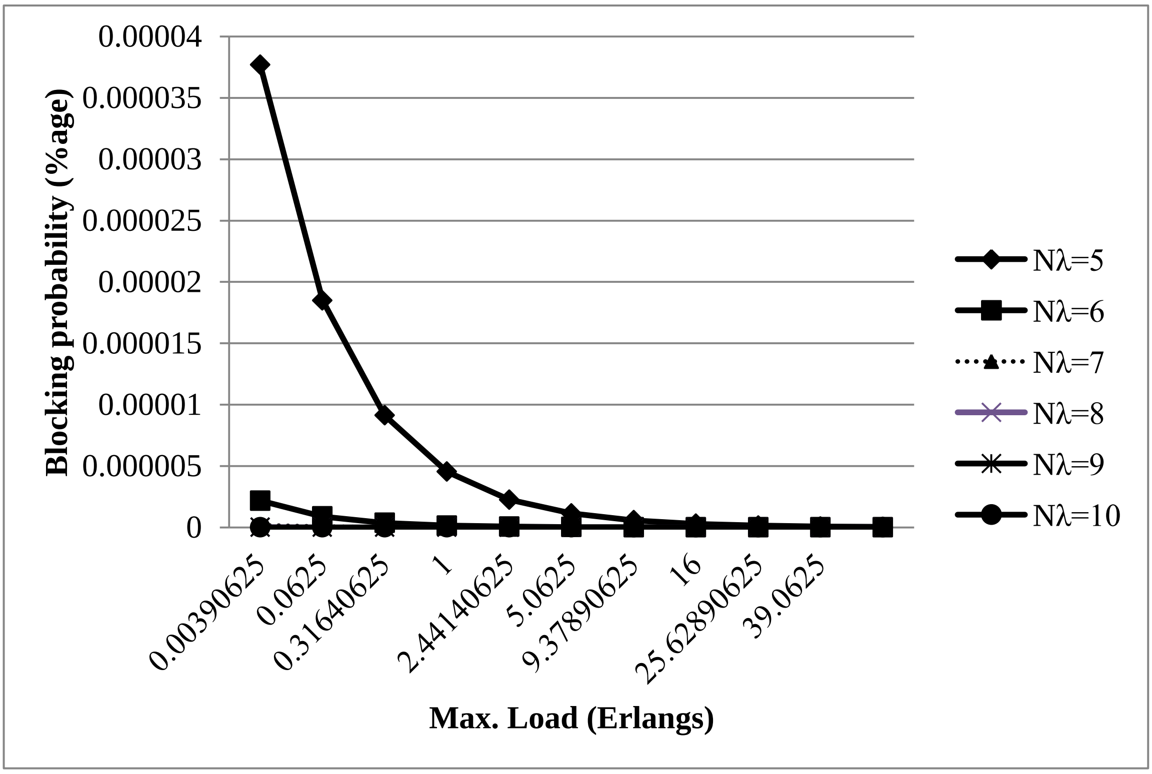


Figure 3.9: Blocking probability vs Max. load for Model-II
(for wavelength non-convertible networks)

Table 3.3: Blocking probability (%age) for Model-II

No. of links	**Total Number of Free Wavelengths**							
	Nλ=3	**Nλ=4**	**Nλ=5**	**Nλ=6**	**Nλ=7**	**Nλ=8**	**Nλ=9**	**Nλ=10**
3	2.66667	0.90402	0.37784	0.18116	0.09580	0.05455	0.03292	0.02082
4	1.50410	0.36645	0.11644	0.04399	0.01881	0.00883	0.00447	0.0024
5	0.96777	0.17392	0.04313	0.01315	0.00464	0.00183	0.00079	0.00036
6	0.66735	0.08949	0.01758	0.00440	0.00130	0.00044	0.00016	6.6E-05
7	0.48061	0.04827	0.00756	0.00157	0.00039	0.00011	3.7E-05	1.3E-05
8	0.35694	0.02688	0.00337	0.00058	0.00012	3.1E-05	9.0E-06	2.8E-06
9	0.27136	0.01533	0.00153	0.00022	4.1E-05	8.9E-06	2.3E-06	6.4E-07
10	0.21013	0.00890	0.00071	8.5E-05	1.3E-05	2.6E-06	5.8E-07	1.5E-07
11	0.16516	0.00525	0.00034	3.4E-05	4.5E-06	7.6E-07	1.5E-07	3.5E-08
12	0.13142	0.00313	0.00016	1.3E-05	1.5E-06	2.3E-07	4.0E-08	8.3E-09
13	0.10566	0.00189	7.7E-05	5.4E-06	5.3E-07	6.9E-08	1.1E-08	2E-09
14	0.08571	0.00115	3.8E-05	2.2E-06	1.8E-07	2.1E-08	2.9E-09	4.9E-10
15	0.07005	0.00070	1.8E-05	9.0E-07	6.5E-08	6.4E-09	8E-10	1.2E-10
16	0.05763	0.00043	9.1E-06	3.7E-07	2.3E-08	2.0E-09	2.2E-10	2.9E-11
17	0.04770	0.00027	4.5E-06	1.5E-07	8.1E-09	6.1E-10	6.0E-11	7.3E-12
18	0.03968	0.00017	2.3E-06	6.3E-08	2.9E-09	1.9E-10	1.7E-11	1.8E-12
19	0.03316	0.00010	1.1E-06	2.6E-08	1.0E-09	6.0E-11	4.7E-12	4.6E-13
20	0.02783	6.6E-05	5.7E-07	1.1E-08	3.7E-10	1.9E-11	1.3E-12	1.1E-13
21	0.02344	4.2E-05	2.9E-07	4.6E-09	1.3E-10	6.0E-12	3.7E-13	2.9E-14
22	0.01981	2.6E-05	1.5E-07	2.0E-09	4.9E-11	1.9E-12	1.0E-13	7.4E-15
23	0.01679	1.7E-05	7.4E-08	8.3E-10	1.8E-11	6.0E-13	2.9E-14	1.9E-15

and P_{BC}^{r} i.e. blocking probability caused by insufficient wavelength and blocking probability caused by lack of converter. The expression (3.16) represents that blocking probability depends on the total number of wavelengths available, number of links in the route selected, load on the route r and number of converters used in the network. The blocking probability of network has been calculated according to this model (Model-III) for wavelength–routed all–optical wavelength convertible networks. We have used sparse wavelength conversion and calculated variation of blocking probability of the network with load and number of total wavelengths available in that network.

Table (3.4) shows the value of blocking probability of wavelength convertible network for a particular load (per link) with total number of wavelengths used in network for Model-III. It is clear from the table that blocking probability of network for Model-III increases with load but it significantly decreases with increase in total number of wavelengths used in the network. Figure (3.11) and figure (3.13) shows graphically blocking probability distribution of wavelength convertible network with variation of load. The results shown in figure (3.12) clearly depicts that blocking probability of system is high for higher values of load but its value decreases to a value comparable to zero when total number of wavelengths available is increased from 1 to 5. This number of wavelengths can be easily achieved hence blocking probability of the system is reduced to a very small value using this model.

Table 3.4: Blocking probability (%age) for Model-III

Load	**W=1**	**W=2**	**W=3**	**W=4**	**W=5**
1	50	20	6.25	1.538462	0.306748
2	66.66667	25	6.896552	1.587302	0.309119
3	75	27.27273	7.142857	1.604278	0.309917
4	80	28.57143	7.272727	1.612903	0.310318
5	83.33333	29.41176	7.352941	1.618123	0.310559
6	85.71429	30	7.407407	1.621622	0.31072
7	87.5	30.43478	7.446809	1.62413	0.310835
8	88.88889	30.76923	7.476636	1.626016	0.310921
9	90	31.03448	7.5	1.627486	0.310988
10	90.90909	31.25	7.518797	1.628664	0.311042
20	95.2381	32.25806	7.604563	1.633987	0.311284
30	96.77419	32.6087	7.633588	1.635769	0.311365
40	97.56098	32.78689	7.648184	1.636661	0.311405
50	98.03922	32.89474	7.656968	1.637197	0.311429
100	99.0099	33.11258	7.674597	1.63827	0.311478
200	99.50249	33.22259	7.683442	1.638807	0.311502
500	99.8004	33.28895	7.688759	1.639129	0.311517

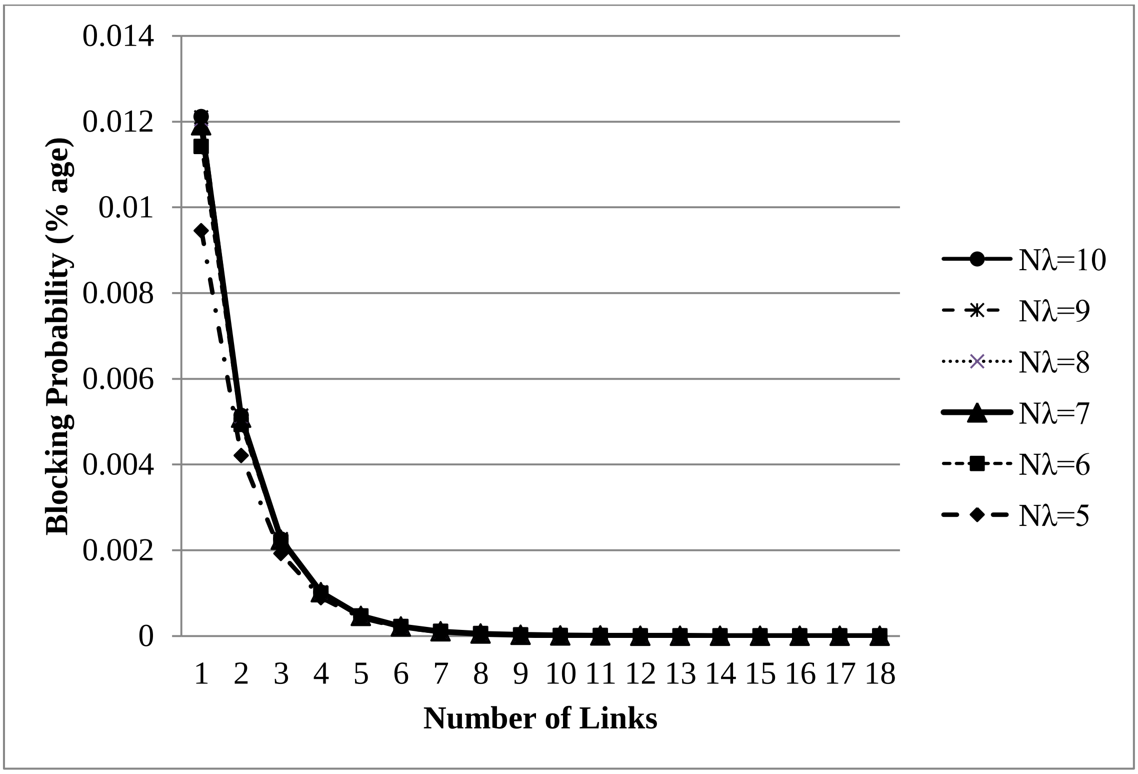


Figure 3.10: Blocking probability vs Number of links for wavelength convertible networks (Model-II)

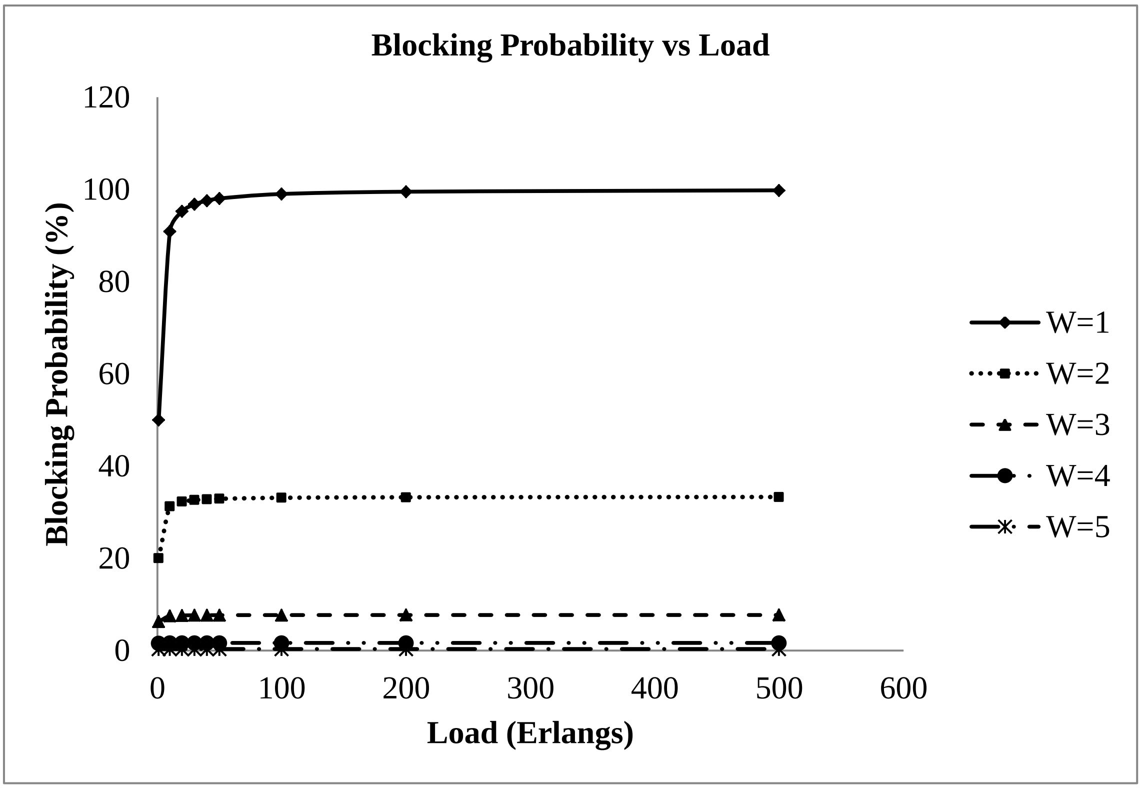


Figure 3.11: Blocking probability vs Load for Model-III.

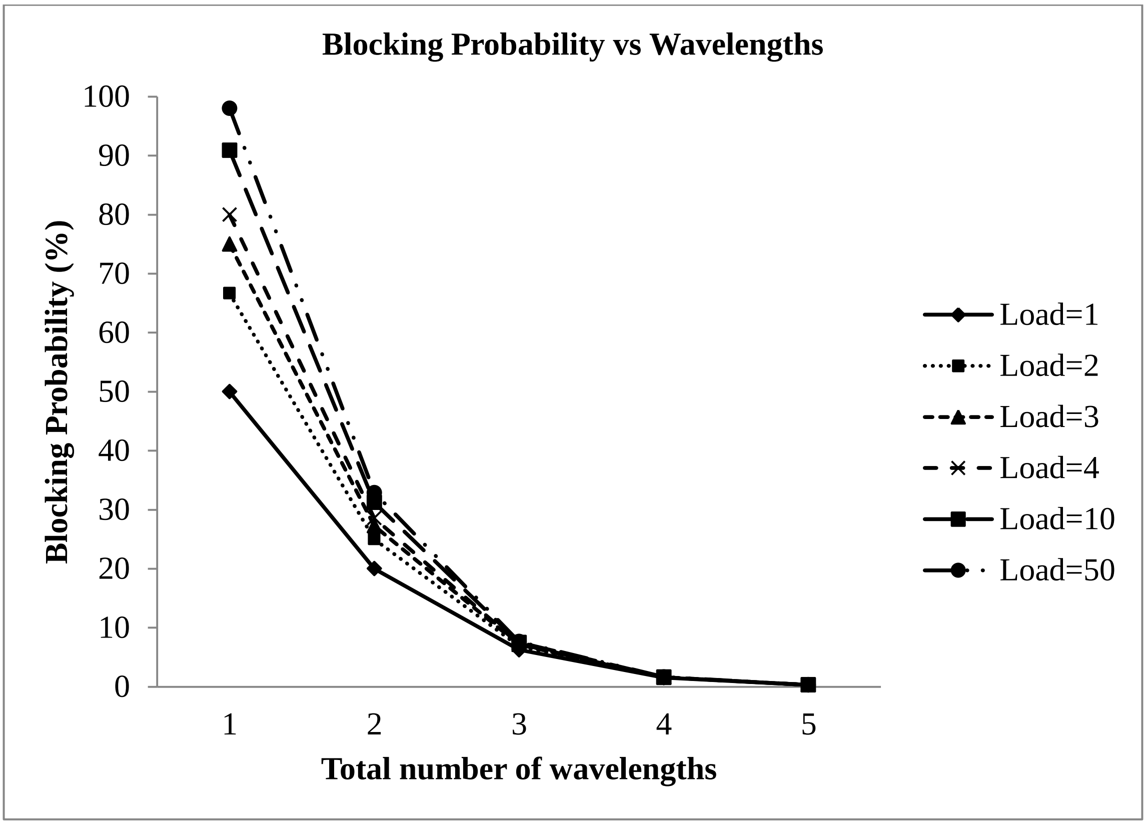


Figure 3.12: Blocking probability vs Number of wavelengths for Model-III

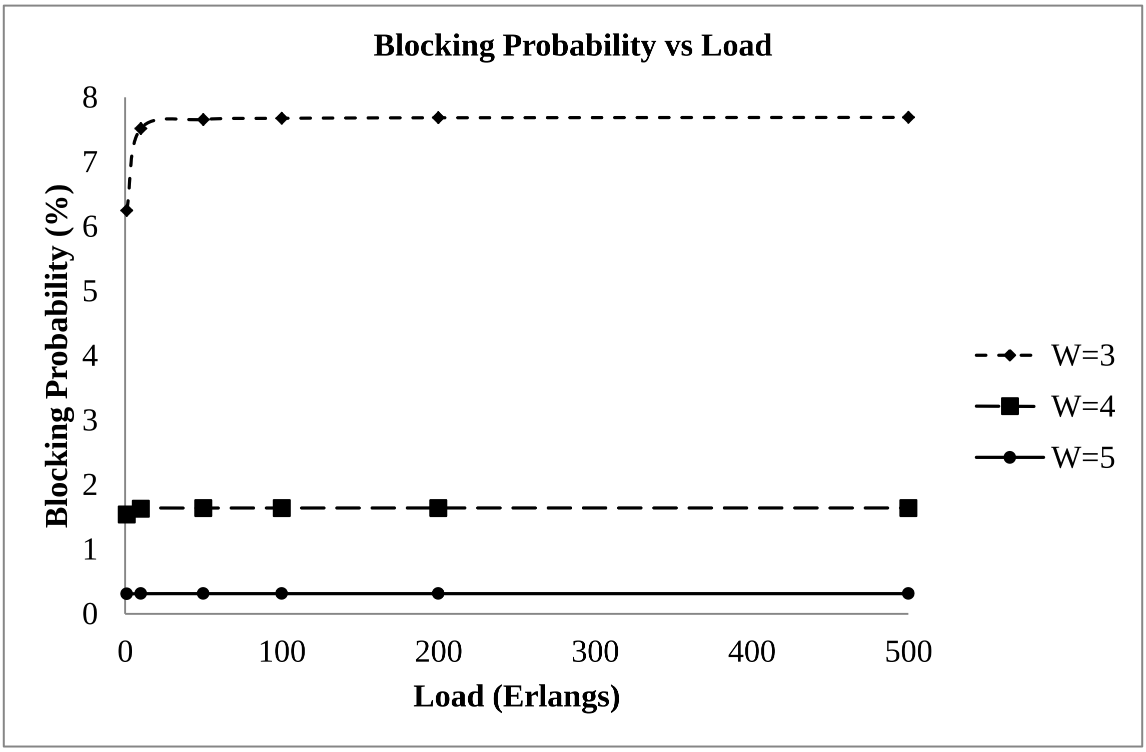


Figure 3.13: Blocking probability vs Load with different wavelengths for Model-III

Table: 3.5: Blocking probability for a given route length for Model-IV

Nλ	**L=1**	**L=5**	**L=10**	**L=15**	**L=20**	**L=25**
1	1.01378E-07	1.2E-13	0	0	0	0
2	3.81902E-05	9.685E-11	2.3E-13	1E-14	0	0
3	0.000810388	4.57238E-09	1.205E-11	3.5E-13	3E-14	0
4	0.005307549	6.6477E-08	1.937E-10	5.76E-12	4.6E-13	6E-14
5	0.01838457	5.06888E-07	1.63226E-09	5.016E-11	4.09E-12	5.8E-13
6	0.043141838	2.5696E-06	9.14477E-09	2.9054E-10	2.411E-11	3.44E-12
7	0.078740883	9.82819E-06	3.86555E-08	1.26977E-09	1.0714E-10	1.542E-11
8	0.121661064	3.05866E-05	1.32954E-07	4.51535E-09	3.8739E-10	5.632E-11
9	0.167963226	8.13185E-05	3.90658E-07	1.37172E-08	1.19663E-09	1.7573E-10
10	0.214582343	0.000190936	1.01378E-06	3.68032E-08	3.26452E-09	4.8424E-10
20	0.603723019	2.27108E-05	4.43892E-08	1.15473E-09	8.67E-11	1.164E-11
30	0.681335974	0.197882802	0.008074392	0.000572699	7.09126E-05	1.28479E-05
50	0.804716497	0.701115563	0.169358237	0.024700749	0.004305938	0.00095432
60	0.836518205	0.834228335	0.356608001	0.076722333	0.016083588	0.00395526
70	0.86098994	0.933647227	0.628733289	0.191617877	0.046732469	0.01254023
80	0.87673029	0.945202341	0.726711505	0.319130185	0.100965329	0.03115802
90	0.890240382	0.966658867	0.840989716	0.483924213	0.19021772	0.06667991
100	0.901084705	0.978943655	0.910668093	0.640097238	0.310034261	0.12457176

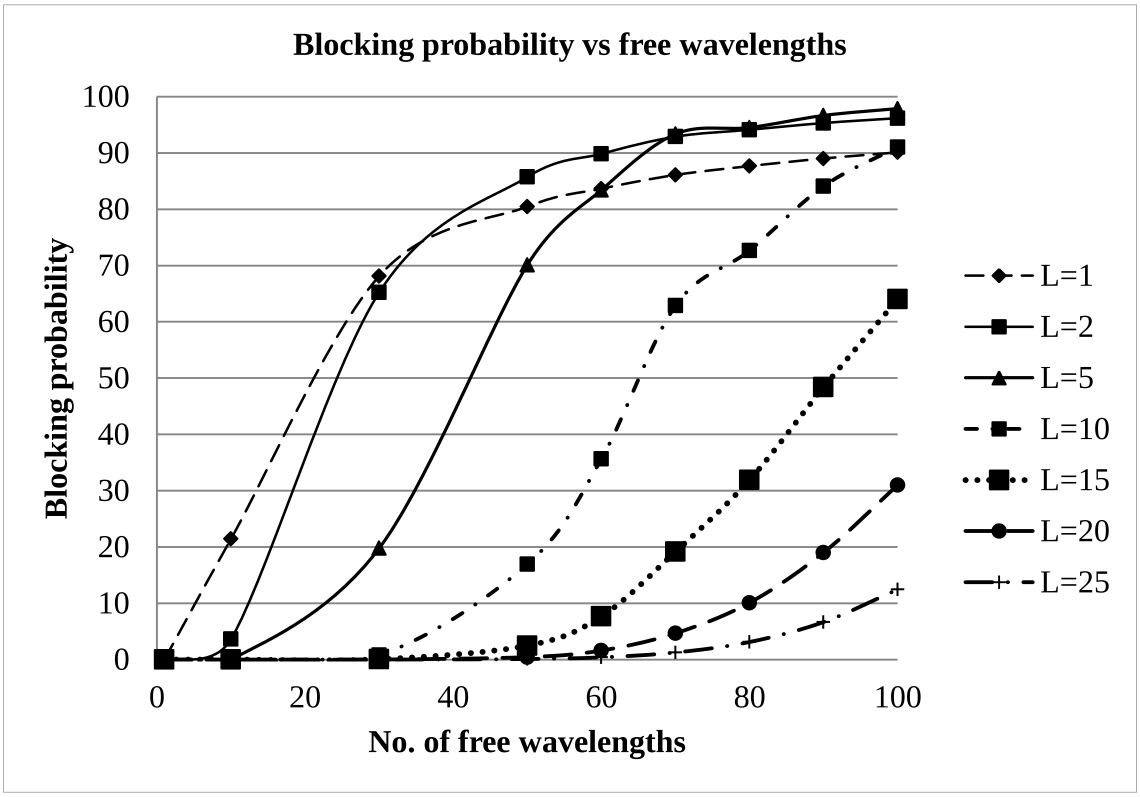


Figure 3.14: Blocking probability vs number of free wavelengths for Model-IV

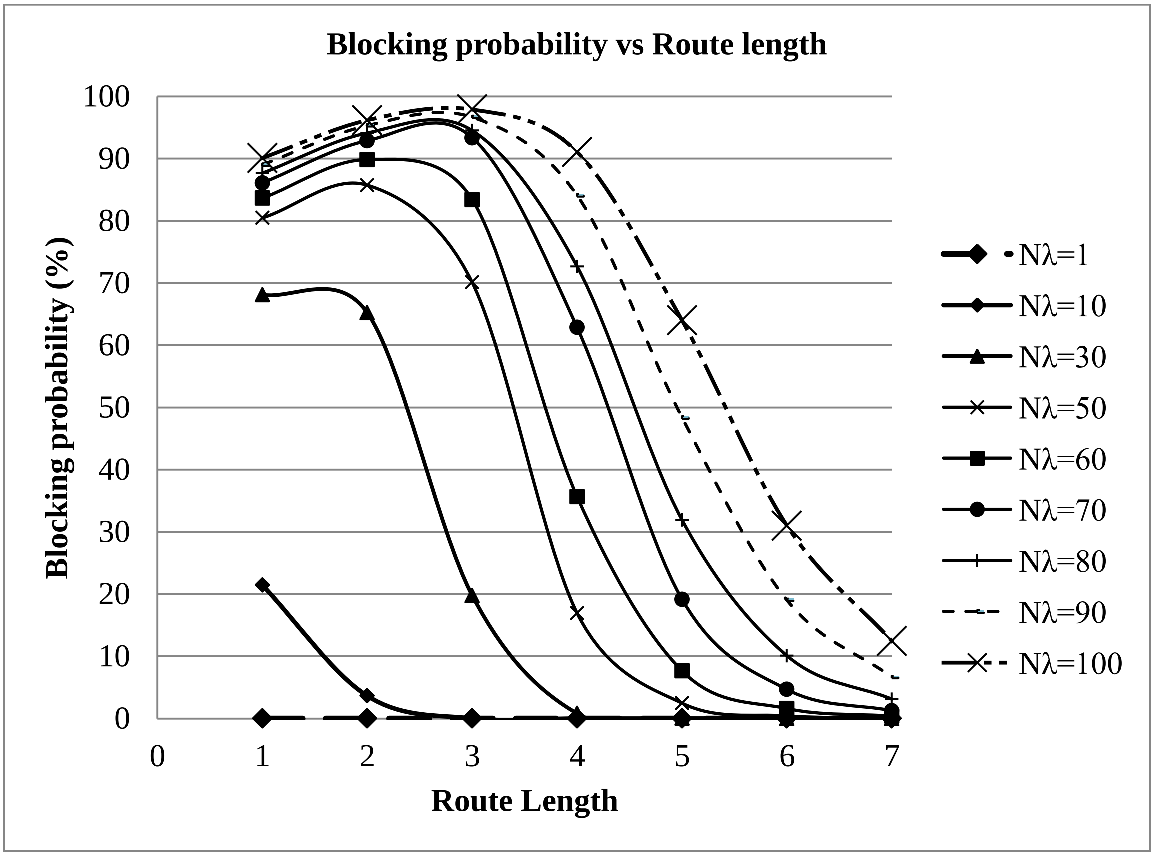


Figure 3.15: Blocking probability vs Route length for Model-IV

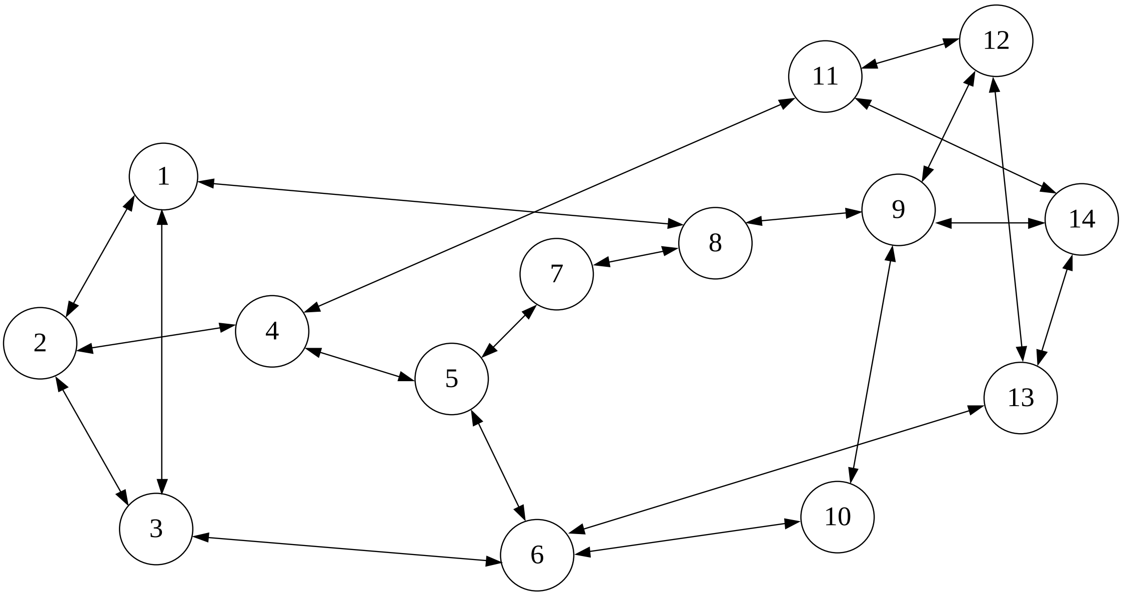


Figure 3.16: NSFnet network topology (14-node, 21-links)

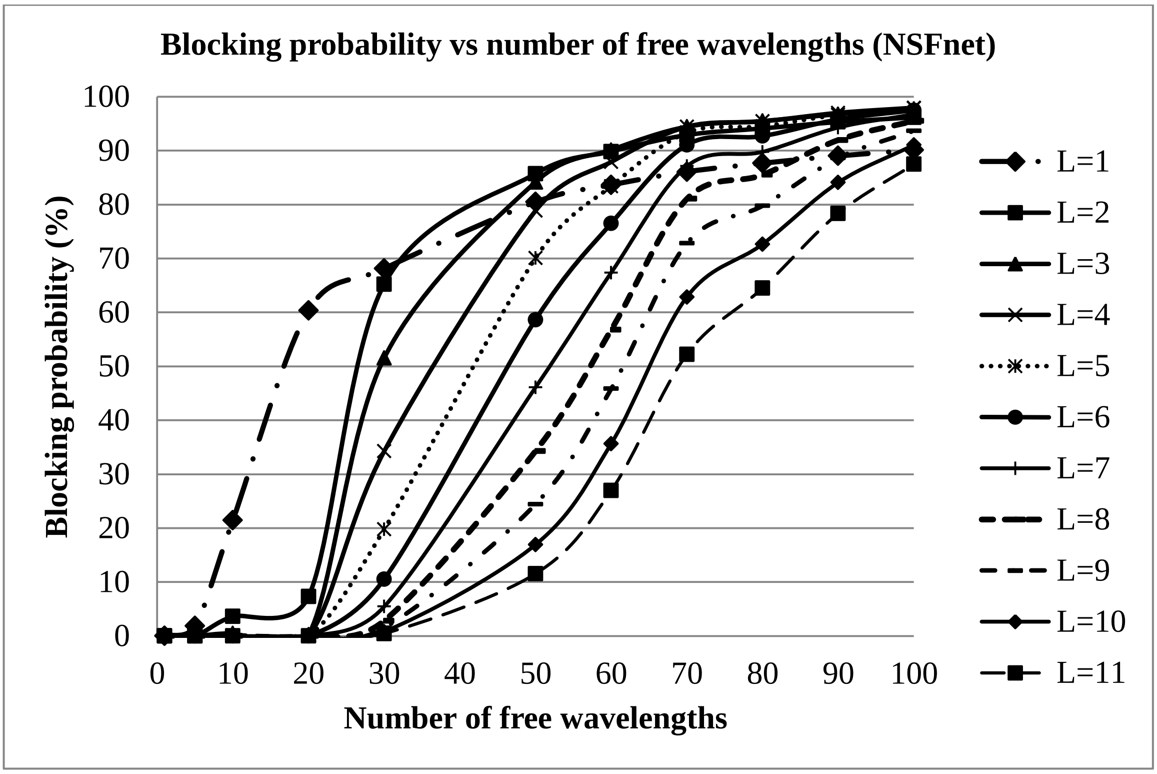


Figure 3.17: Blocking probability vs number of free wavelengths (NSFnet) for Model-IV

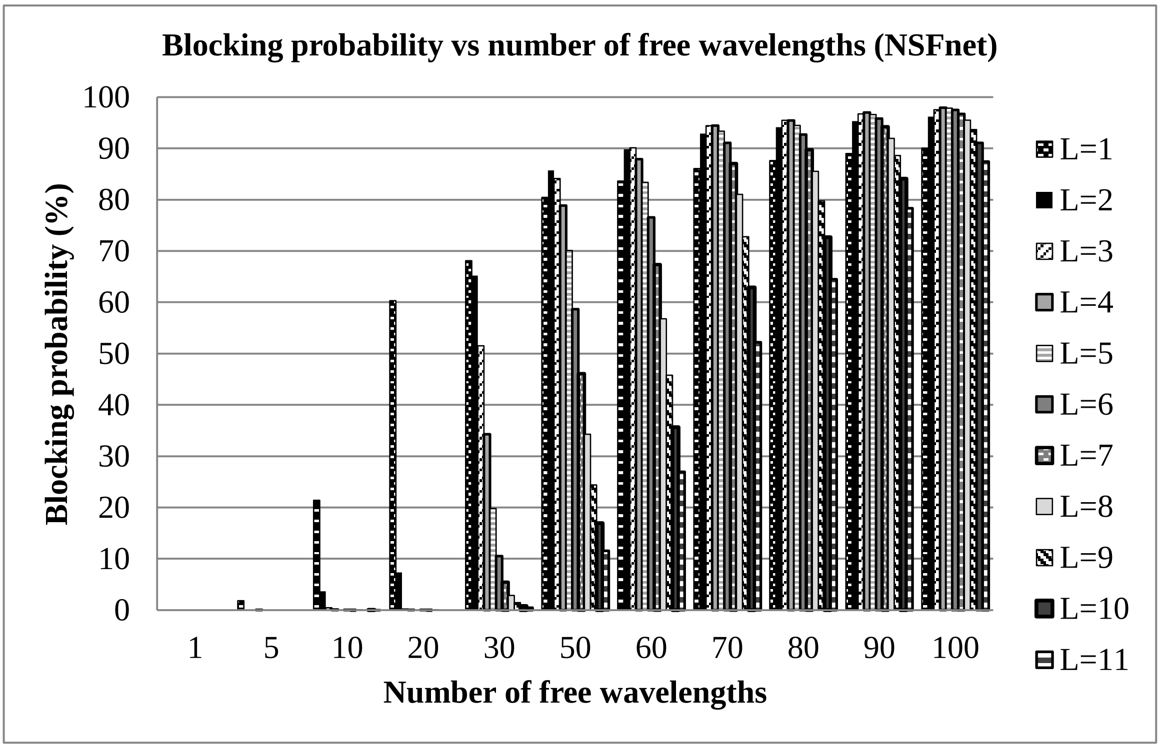


Figure 3.18: Blocking probability vs number of free wavelengths (NSFnet) for Model-IV

3.3.3. Wavelength Convertible and Non-Convertible WDM Networks (Model-IV)

The blocking probability of network depends on number of free wavelengths ($N\lambda$), number of channels (C) and length of route (l). We have fixed number of channels (C) to 10 and calculated results for blocking probability B_{sd}. Table (3.5) shows the variation of blocking probability with number of free wavelengths available. It is clear from table that for this model blocking probability decreases with increase in route length but it increases with increase in number of free wavelengths.

The variation of blocking probability with the number of free wavelengths for different route lengths is shown in figure (3.14) and figure (3.15). This model was implemented on NSFnet network topology with 14-nodes and 21-links. Figure (3.16) shows NSFnet network topology on which the model has been applied and the results calculated are shown in figure (3.17) and figure (3.18). From figure (3.17) and figure (3.18) we can choose the suitable path for the network topology for given number of free wavelengths. It is clear from the figure (3.17) and figure (3.18) that blocking probability is minimum until $N\lambda$ = 30.

Also, we can achieve a compromise between route length and number of wavelengths by selecting a path with route length 7 and by selecting number of free wavelengths to 25. The shortest path in this model can be calculated by any of the shortest path routing algorithm such as Dijkstra algorithm.

3.5. Conclusions

In this chapter, low complexity mathematical models are developed which do not require any simulation statistics. These models have low implementation complexity and computation used is quite efficient. There are different models proposed which can be used for both wavelength convertible networks and wavelength non-convertible networks. One of the models (Model-IV) can be used for both wavelength convertible as well as for non-convertible networks. These models also suggest an optimum path as a solution to routing problem. These models also suggest the appropriate number of wavelengths which should be free in a network to have minimum blocking probability. These models are implemented on different network topologies, such as they are used to evaluate the blocking performance of NSFNet topology and hence used to improve its performance. We can go for a compromise between the path length and number of free wavelength to yield best results in terms of blocking probability. The results proved that Model-III works well for network having higher values of load. Also, we can see from the results that using Model-III we can achieve better results for higher number of wavelengths and for large load per unit link. So, this model can be efficiently implemented on a network where load applied per link is large. The value of blocking probability can be reduced to a very low value comparable to zero using this model. Also the computation efficiency of proposed models is very high as compared to the existing models.

CHAPTER IV

WAVELENGTH CONVERSION AND ASSIGNMENT STRATEGIES

Publications from chapter

1. Amit Wason, R. S. Kaler, "Blocking performance analysis of wavelength assignment algorithms in WDM networks," *International Journal of Microwave and Optical Technology*, vol. 3, no. 1, pp. 54-61, January 2008.
2. Amit Wason, R. S. Kaler, "Wavelength Assignment Algorithms for WDM optical networks," *Optik -International Journal for Light and Electron Optics-Elsevier Science*, vol. 122, no. 10, pp. 877-880, May 2011.

In this chapter, we have investigated the first objective in order to analyse and develop wavelength assignment algorithms. The models proposed in the previous chapter are used in this chapter to develop wavelength assignment strategies. The effective algorithms are proposed in this chapter and the performance of new wavelength assignment algorithms is evaluated in terms of blocking probability and fairness. In the first section of this chapter, the analysis of conventional wavelength assignment algorithms has been discussed. These algorithms are compared on the basis of blocking probability, number of channels and the number of links are kept constant whereas the response of algorithms is calculated by varying load (in Erlangs) per unit link. In the second section, two new wavelength assignment algorithms have been developed. Further, the results of these proposed algorithms are compared with conventional wavelength assignment algorithms such as first-fit, best-fit, random and most-used wavelength assignment algorithms. These simulation results show that the proposed approaches are very effective for minimization of blocking probability of optical WDM networks.

4.1. Analysis of Conventional Wavelength Assignment Strategies.

In this section, conventional wavelength assignment strategies are analysed and compared with each other on the basis of blocking probability and fairness. The performance of conventional wavelength assignment algorithms is calculated in terms of blocking probability and fairness. Erlang’s-B formula is used to compute the blocking probability. We have developed approximate analytical models for clear channel blocking probability of the network with arbitrary topology, both with or without wavelength translations. The goal of our analysis is to calculate and compare blocking probability of different algorithms. In order to do the analysis following assumptions are made:

- The network is connected in an arbitrary topology. Each link has a fixed number of wavelengths.
- Each station has an array of transmitters and receivers, where W is the number of wavelengths carried by the fiber.
- Point to point traffic.
- There is no queuing of the connection request. The connection blocked will suddenly be discarded.
- Link loads are mutually independent.
- Static routing is assumed.

We have considered blocking probability for wavelength non-convertible networks. The two constraints which are followed for the wavelength assignment are:

1. Wavelength continuity constraint: a lightpath must use the same wavelength on all links along the path from source to destination edge nodes.

2. Distinct wavelength constraint: all lightpaths using the same link must be allocated distinct wavelengths.

If there is no free wavelength available on any link the call will be blocked. In simple terms blocking probability as per *Poisson’s formula* can be calculated as the ratio of calls blocked to the total number of calls generated as given in equation (4.1).

$$P_{Bavg} = \frac{Total\ number\ of\ calls\ blocked}{Total\ number\ of\ calls\ generated} \tag{4.1}$$

Also, the blocking probability on the link can be calculated by famous Erlang-B formula as given by Milan Kovacevic [111] equation (4.2)

$$P_{b(L,W)} = \frac{\frac{L^W}{W!}}{\sum_{i=0}^{W}\frac{L^i}{i!}} \tag{4.2}$$

Where $P_{b(L,W)}$ is blocking probability for L load and W wavelengths.

4.1.1. Conventional Algorithms

The algorithms which are used for simulation are conventional algorithms such as first-fit algorithm and random algorithm. These algorithms can be illustrated as below:

1. *First-fit algorithm*: In this algorithm, firstly the wavelengths of the traffic matrix are sorted in non-decreasing order. Then algorithm steps through this sorted list for selecting candidate chains joined. Let u_{ij} be the next highest wavelength element in sorted list. Then, if both nodes i and j are the end nodes of two chains, largest chain is formed by joining two ends, otherwise next highest element is considered. This process is carried on until all chains are considered to form a single chain representing linear topology.

2. *Random algorithm*: In this algorithm, wavelength is selected randomly from available wavelengths. A number is generated randomly and the wavelength is assigned to this randomly generated number.

```
Algorithm First-fit
begin
        sort elements of U in non-decreasing order;
        While (two or more chain exist) do
        begin
        let $u_{ij}$ be the next highest element in U;
        if ($i$ and $j$ are the end nodes of the two chains '$ij$' and '$jl$' ) then
                connect $i$ and $j$ to get the chain '$kl$';
        discard $u_{ij}$ ;
end;
```

Figure 4.1: First-fit Algorithm

The algorithm for the random wavelength assignment is very simple and is limited to the generation of a random number but algorithm for first-fit is a bit complex. The algorithm for the first-fit wavelength assignment can be illustrated by figure (4.1).

4.1.2. Simulation Comparison of Conventional Algorithms

In this section, we have presented simulation results for random and first-fit wavelength assignment and wavelength conversion algorithms. In all simulations, blocking probability of conventional algorithms for the network is compared depending upon the number of channels, load and number of links. The number of wavelengths on all links is kept constant. The simulation is carried out on MATLAB 7.2 of Mathworks. In the first case, we have fixed the values of the number of channels C = 11, number of links = 10 and load (in Erlangs) is varied. The results are shown in figure (4.2) – figure (4.3).

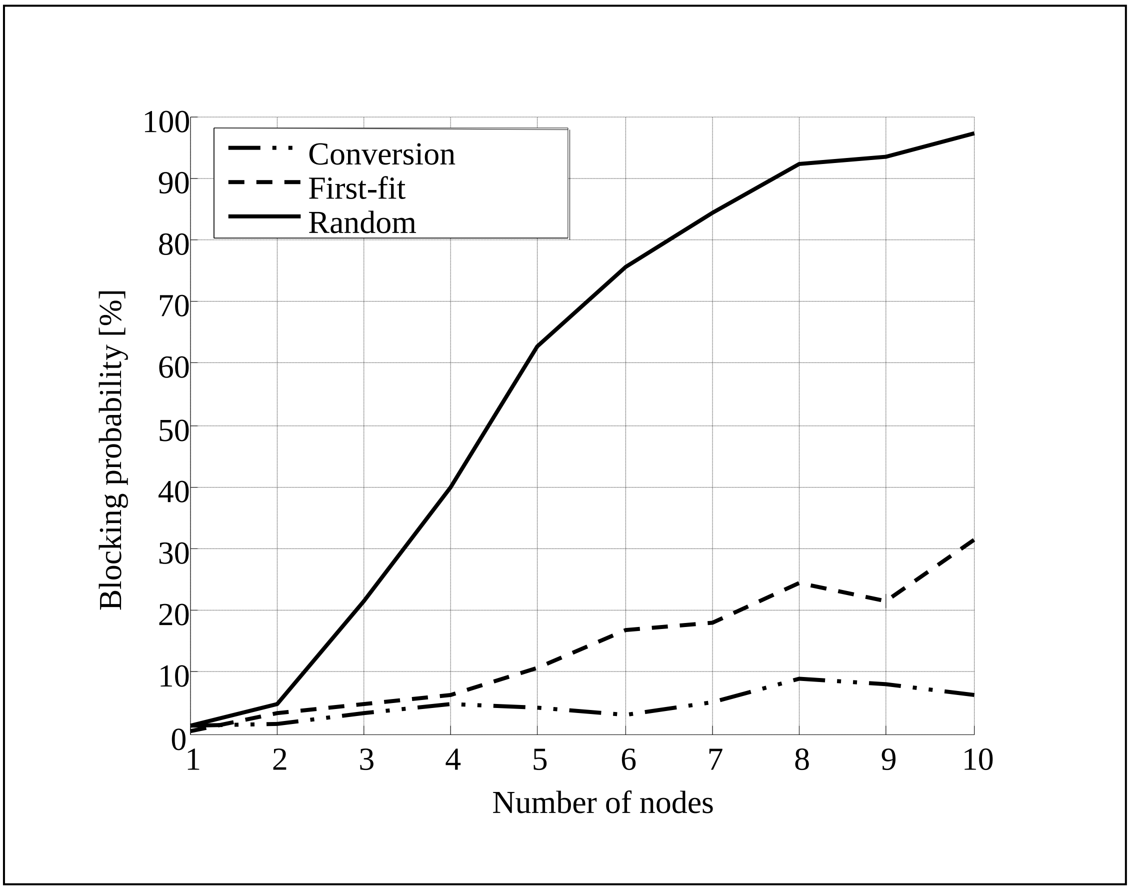


Figure 4.2: Blocking probability of 10 nodes for load 5 Erlangs per link

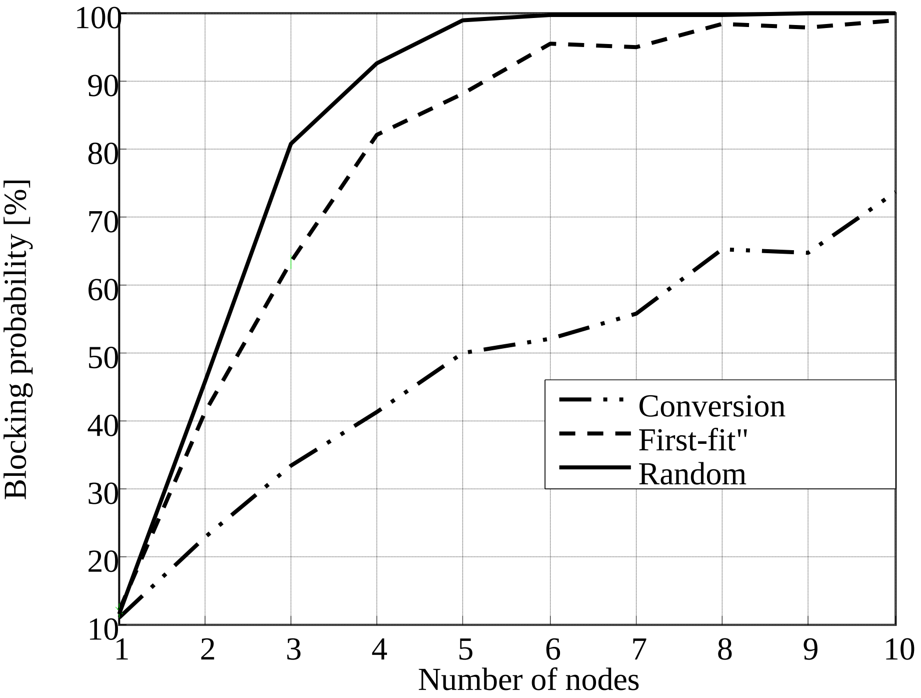


Figure 4.3: Blocking probability of 10 nodes for load 9 Erlangs per link

The simulation results show the blocking probability (%) variation with the number of nodes for different wavelength assignment algorithms. The blocking probability increases with increase in the number of nodes. The blocking probability in case of random algorithm is always greater than that of blocking probability in first-fit wavelength assignment algorithm. The figure (4.2) and figure (4.3) show the variation of blocking probability for 10 nodes; both with wavelength conversion as well as without wavelength conversion with load varying from 5 Erlangs to 9 Erlangs per unit link. The results show that blocking probability is least in case of wavelength conversion, whereas first-fit wavelength assignment algorithm has better results as compared to random wavelength assignment algorithms.

4.2. Proposed Most-Used Wavelength Conversion Algorithm

In this section, we have proposed an efficient wavelength assignment algorithm for dynamic provisioning of lightpath. This proposed algorithm is an improvement of most-used wavelength assignment algorithm. We have used mathematical model (Model-I) for WDM optical networks for minimization of blocking probability. The results of proposed algorithm and Model-I given by equation (3.7) are then compared with conventional wavelength assignment algorithms such as first-fit, best-fit, random and most used wavelength assignment algorithms. Simulation results proved that these proposed approaches are very effective for minimization of blocking probability of optical WDM networks.

4.2.1. Analytical Model

In this section, the framework of random, first-fit and most-used wavelength assignment algorithms is covered. We have developed approximate analytical models for the clear channel blocking probability of network with arbitrary topology, both with or without wavelength translations. The goal of our analysis is to calculate and reduce the blocking probability. In order to do the analysis following assumptions have been made:

- Each station has an array of transmitters and receivers, where W is the wavelengths carried by the fiber.
- Point-to-point traffic.
- There is no queuing of connection request. The connection blocked will suddenly be discarded.
- Link loads are mutually independent.

A. Analysis of wavelength assignment algorithms

For no wavelength translation; the two constraints are to be followed for wavelength assignment these are wavelength continuity constraint and distinct wavelength assignment constraint. If there is no free wavelength available on any link the call will be blocked. The blocking of calls can be calculated by blocking probability which can be calculated by equation (4.1). In addition, blocking probability on a link can be calculated by the famous Erlang-B formula as in equation (4.2). The algorithms which are used for simulation are first-fit algorithm, best-fit algorithm, most-used algorithm and random algorithm.

B. Most–used wavelength conversion (MUWC) algorithm

This algorithm is an improvement of most–used wavelength assignment algorithm. In this algorithm most–used wavelength assignment algorithm is executed until blocking occurs. When the call is blocked wavelength conversion is introduced and hence blocking probability is reduced. If the full wavelength conversion is used after most–used wavelength assignment algorithm the blocking probability is reduced to a very small value, i.e. up to a minimum possible value. As full wavelength conversion is costlier than sparse wavelength conversion so the sparse wavelength conversion is employed in this proposed algorithm. The most–used wavelength conversion algorithm can be easily explained with figure (4.4).

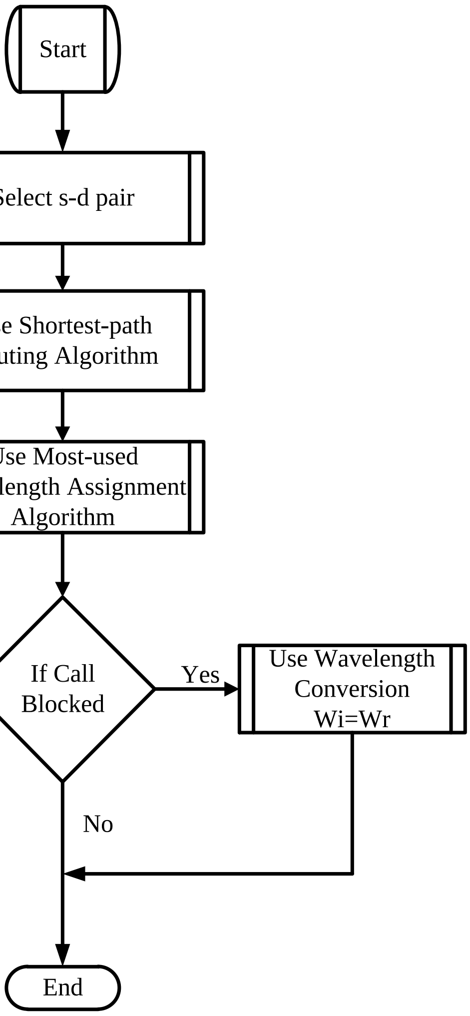


Figure 4.4: Most Used Wavelength Conversion Algorithm

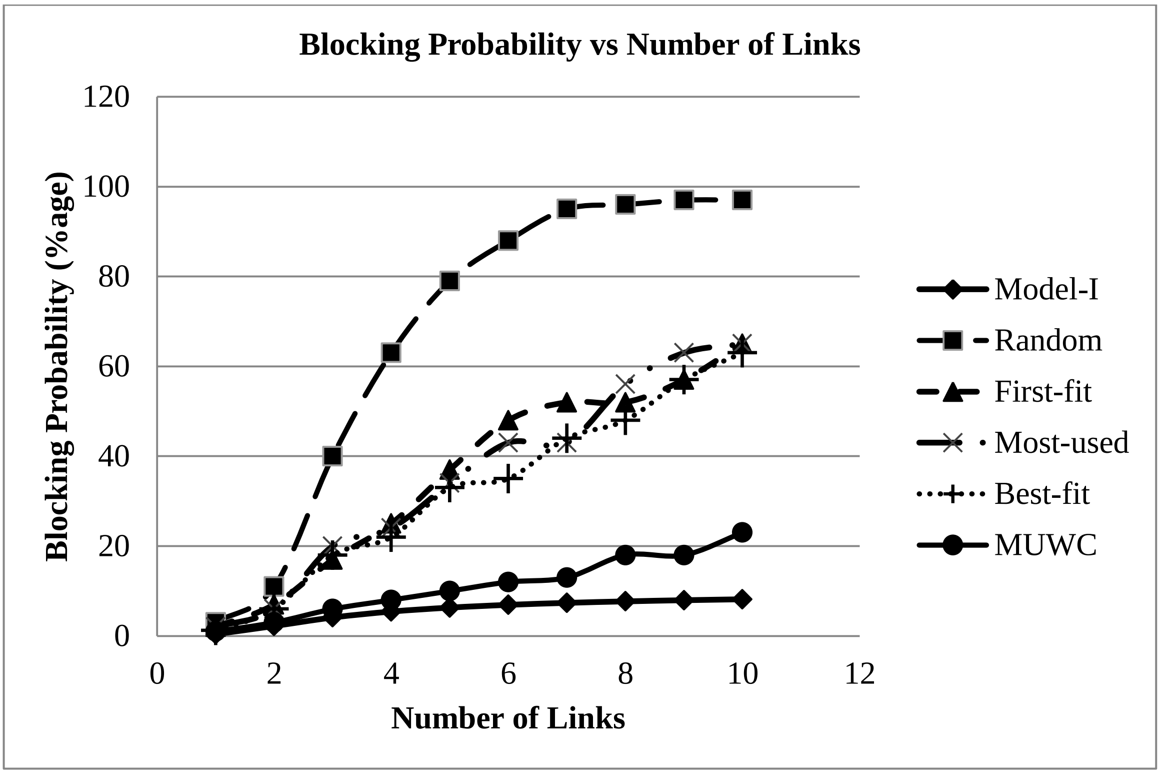


Figure 4.5: Comparison of different wavelength assignment algorithms (Blocking probability (%age) vs number of links for load 6 Erlangs)

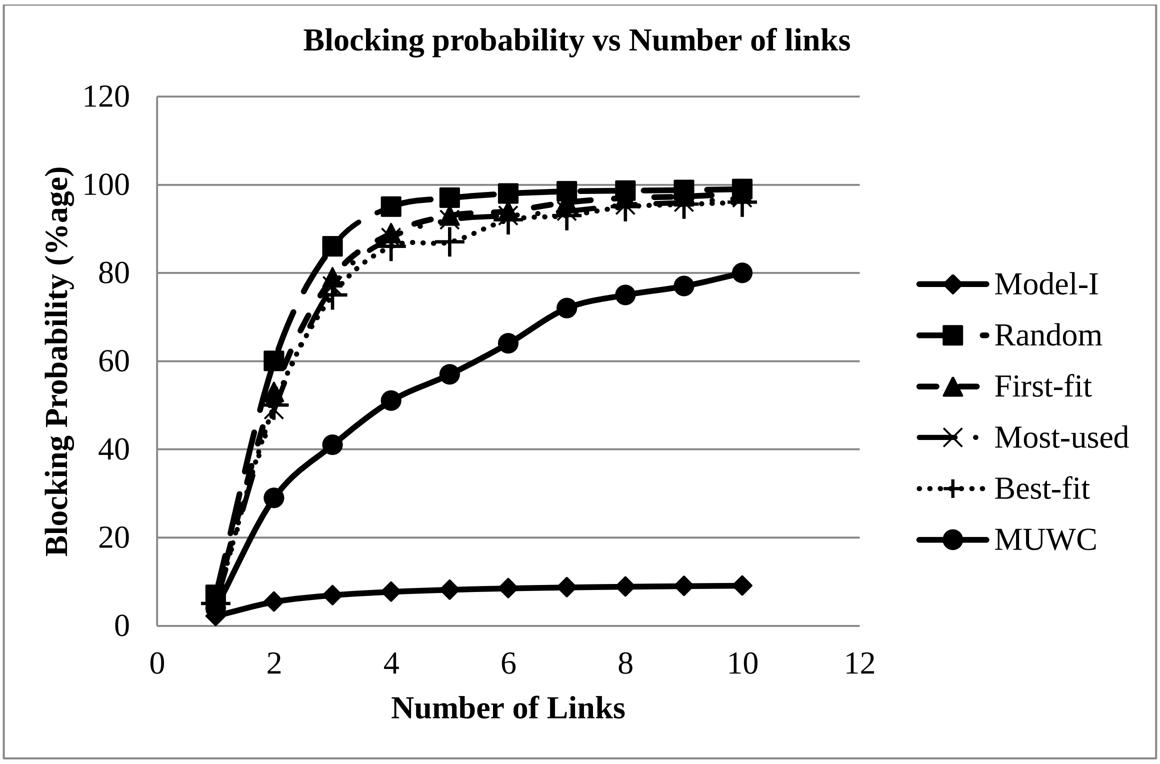


Figure 4.6: Comparison of different wavelength assignment schemes (Blocking probability (%age) vs number of links for load 10 Erlangs)

4.2.2. Results and Discussion

The Most Used Wavelength Conversion algorithm has been proposed for wavelength assignment and the performance of this wavelength assignment algorithm along with the mathematical model (Model-I) is evaluated in terms of blocking probability and fairness. The blocking probability of proposed algorithm and Model-I are compared with algorithms such as first-fit, best-fit, random and most-used wavelength assignment algorithm and are shown in figure (4.5) and figure (4.6).

The results prove that blocking probability of network is highest for random wavelength assignment algorithm and is lowest for Model-I. The blocking probability of proposed algorithm is also very low as compared to the conventional algorithms. Thus, in situations where the mathematical model of the given system can be changed the Model-1 can be used, but if mathematical model cannot be changed one can go for a simple proposed wavelength assignment algorithm (MUWC). The combination of both the proposed model and algorithm can also be used.

```
Algorithm first-fit wavelength conversion
Begin
Sort elements of U in non decreasing order;
While (two or more chain exist) do
        Begin
                let uij be the next highest element in U;
                if (i and j are the nodes of chain ‘ij’ and ‘jl’)
                        then connect i and j to get chain ‘kl’;
                                if (call blocked)
                                then (Wi=Wk)
                                discard uij;
end
```

Figure 4.7: First-Fit wavelength conversion algorithm

4.3. Proposed First Fit Wavelength Conversion Algorithm

The new wavelength assignment algorithm is proposed in this section named First–Fit Wavelength Conversion (FFWC) algorithm. This algorithm is an improvement of earlier first–fit wavelength assignment algorithm. In this algorithm, first–fit wavelength

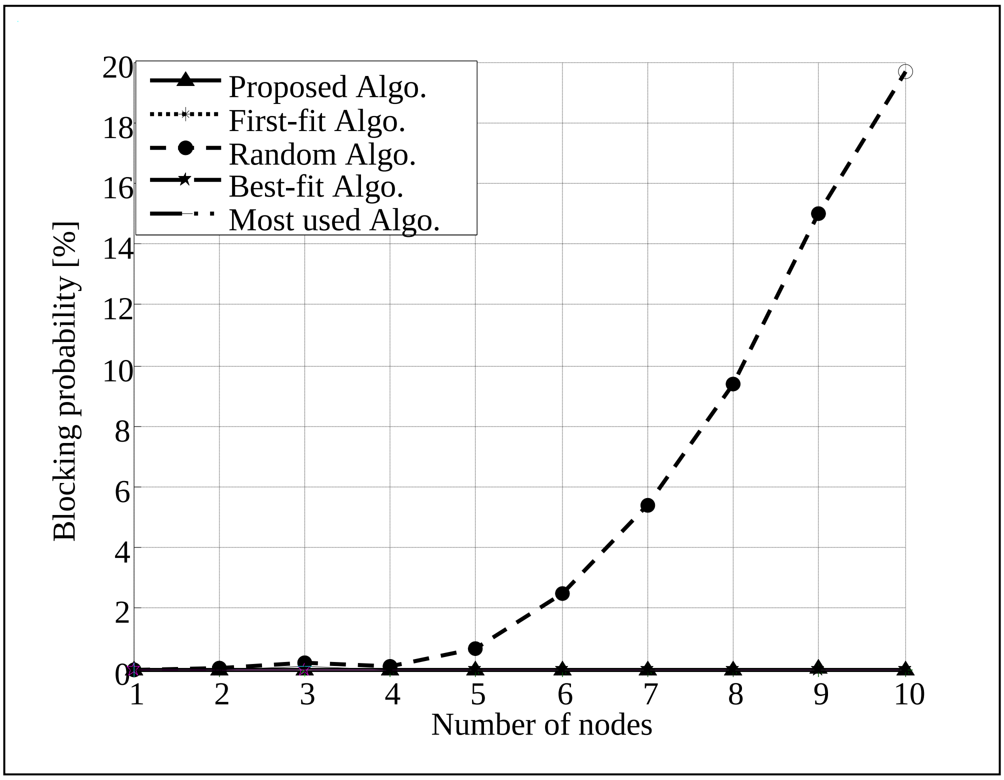


Figure 4.8: Comparison of Algorithms for load 2 Erlangs per link

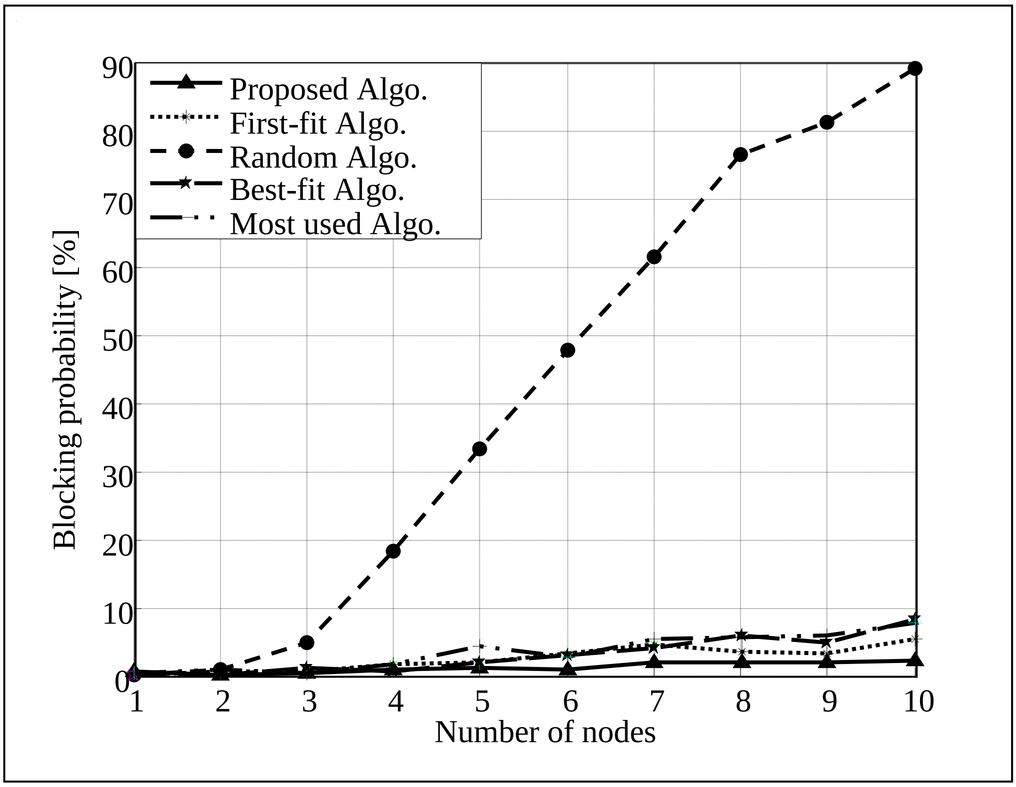


Figure 4.9: Comparison of Algorithms for load 4 Erlangs per link

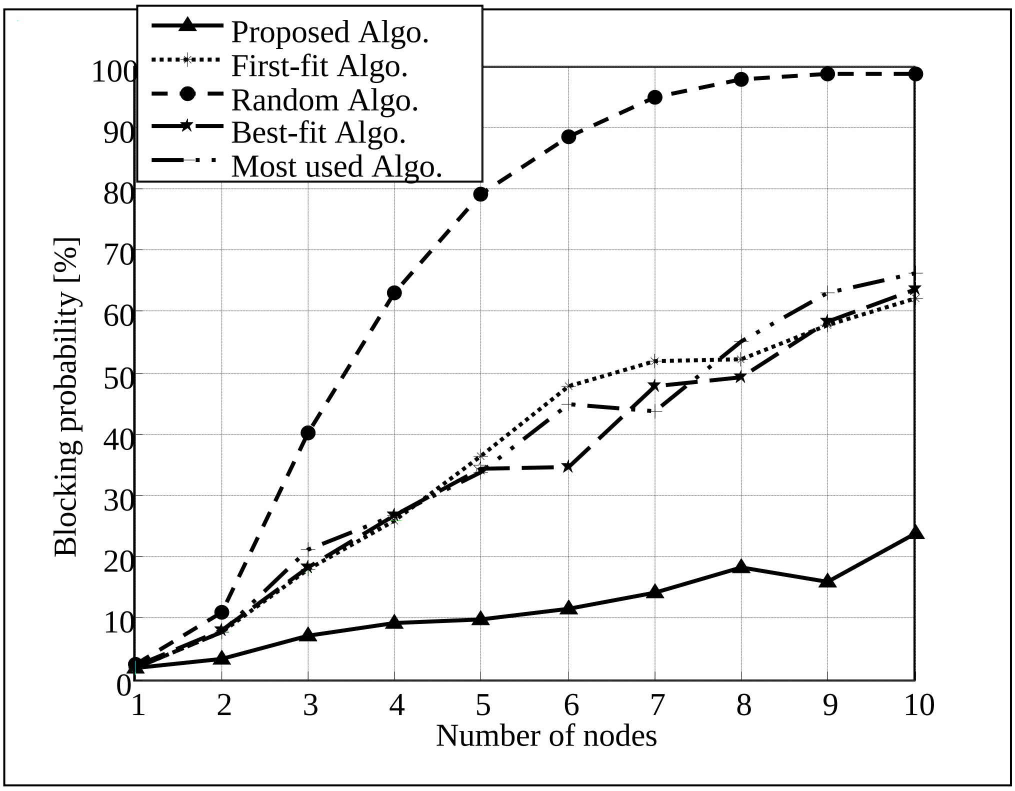


Figure 4.10: Comparison of Algorithms for load 6 Erlangs per link

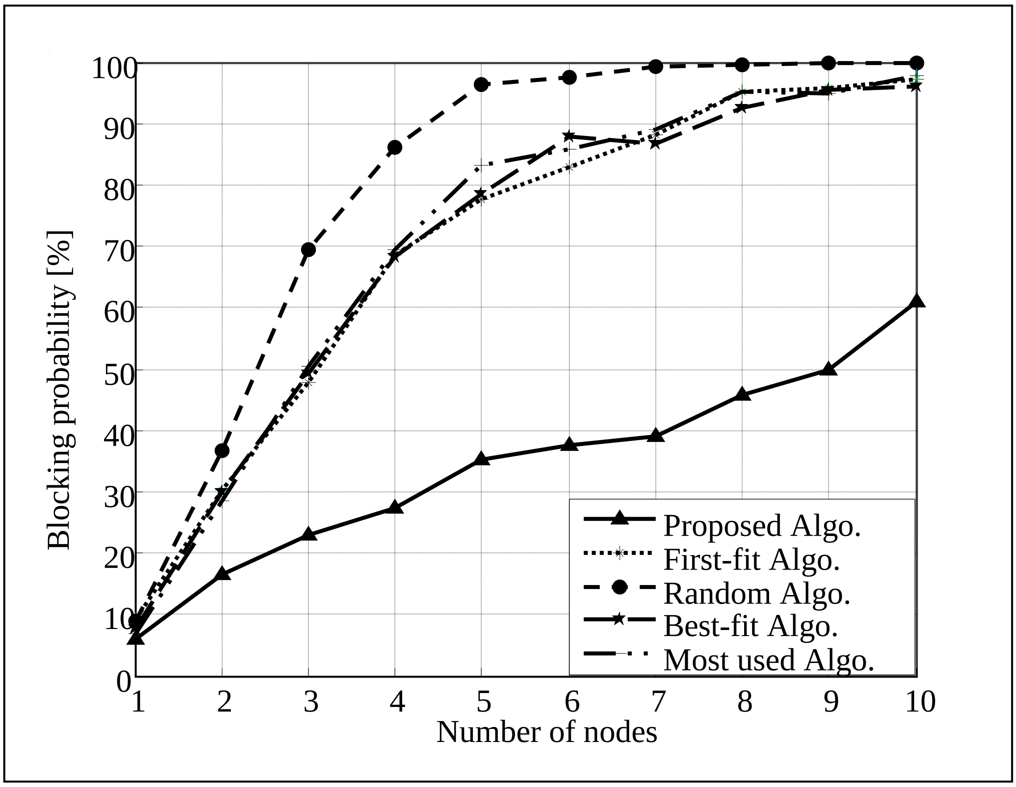


Figure 4.11: Comparison of Algorithms for load 8 Erlangs per link

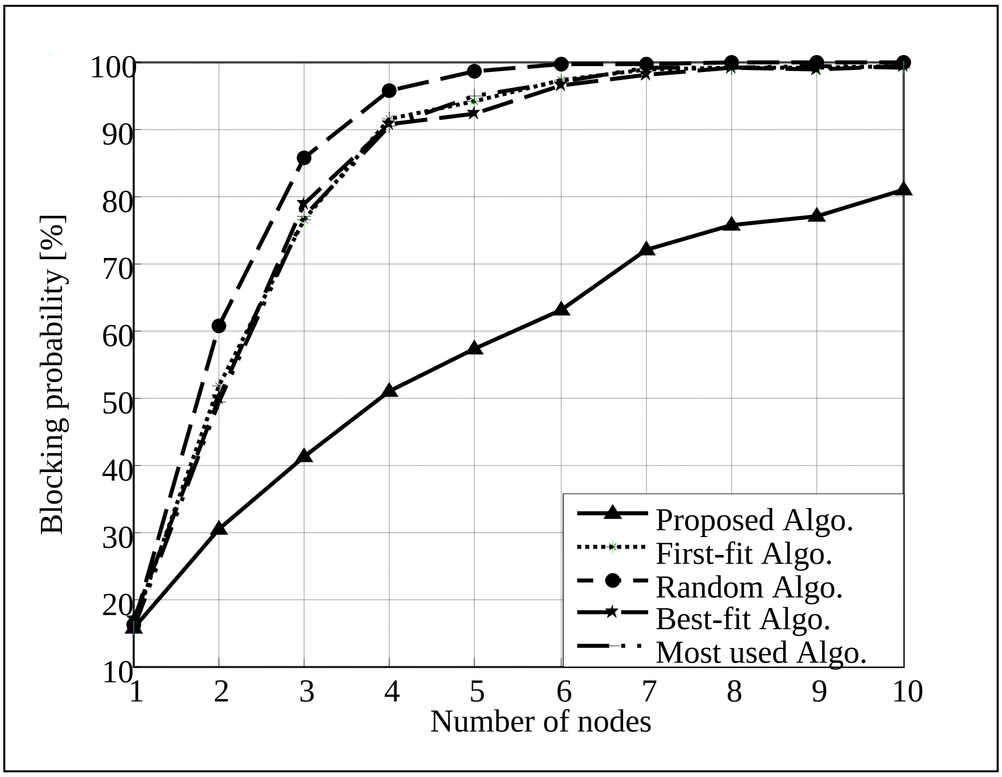


Figure 4.12: Comparison of Algorithms for load 10 Erlangs per link

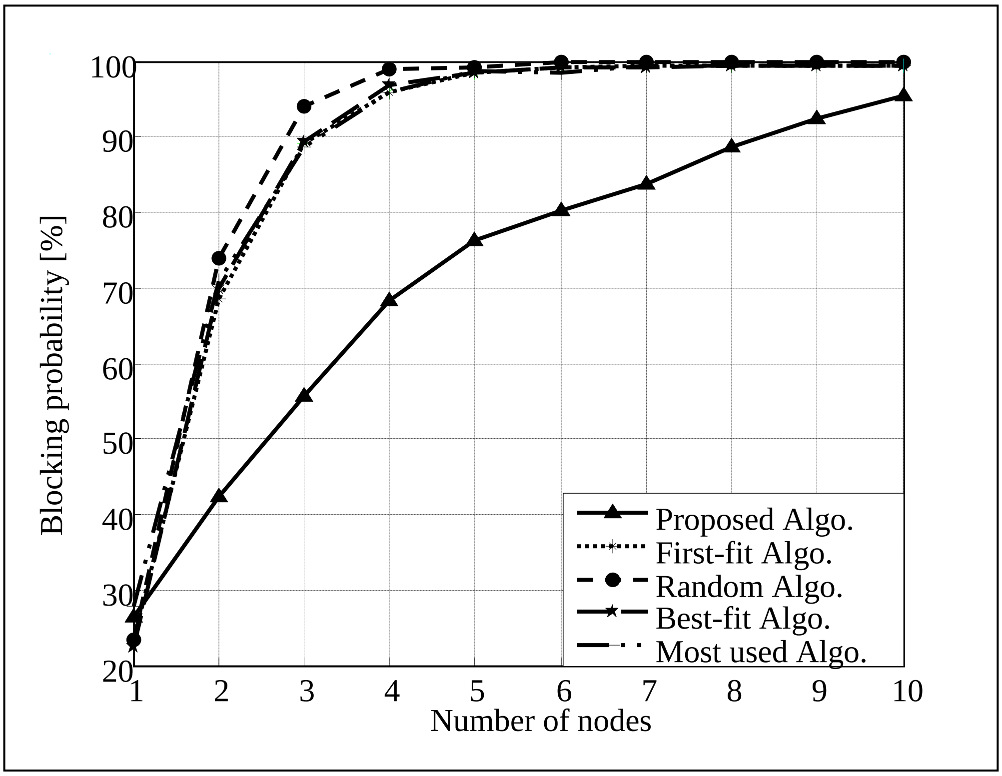


Figure 4.13: Comparison of Algorithms for load 12 Erlangs per link

assignment algorithm is executed until blocking. When the call is blocked, wavelength conversion is introduced and hence blocking probability is reduced. If full wavelength conversion is used after first–fit wavelength assignment algorithm, blocking probability is reduced to near about zero; i.e. blocking probability is reduced to a minimum possible value, whereas by using sparse wavelength conversion blocking probability is reduced to a large extent but is non-zero. Also, full wavelength conversion is costlier than sparse wavelength conversion, so sparse wavelength conversion is employed in this algorithm. The first–fit wavelength conversion algorithm can be easily explained with figure (4.7)

4.3.1. Simulation Results

In this section, the simulation results of proposed first-fit wavelength conversion algorithm have been shown. Also, the blocking probability of FFWC algorithm is compared with the conventional algorithms. The simulation is carried out on a simulation software MATLAB 7.2 of Mathworks. The blocking probability of network is compared depending upon number of channels, load and the number of links. We have fixed values of number of channels $C = 11$, number of links $l = 10$ and load (in Erlangs) is varied. The proposed algorithm is compared with first-fit, best-fit, random and most used wavelength assignment algorithms. The results are shown in figure (4.8) - figure (4.13).

The simulation results proved that blocking probability (%age) increases with increase in the number of nodes. The blocking probability of random algorithm is always greater than blocking probability of other algorithms. The value of blocking probability is always nearly zero for all other algorithms except random algorithm until the load is 2 Erlangs per unit link is applied. The blocking probability increases with the load and is having minimum value in case of proposed algorithm.

4.4. Conclusions

In first section, we have analysed the response of blocking probability of a network having 10 nodes and for varying load for existing wavelength assignment algorithms. The results proved that as the load per link (in Erlangs) increases the blocking probability also increases, the response of first-fit is better than random algorithm whereas response of wavelength conversion is better than without conversion i.e. with first-fit and random algorithm. The comparison of blocking probability of the system has been made for various wavelength assignment algorithms. Two new wavelength assignment strategies FFWC and MUWC; which used sparse wavelength conversion have been proposed which proved to be very effective as compared to conventional algorithms. These wavelength assignment strategies are then compared with the earlier algorithms.

CHAPTER V

ROUTING SCHEMES FOR SURVIVABLE NETWORKS

Publications from chapter

1. Amit Wason, R.S. Kaler, “Rerouting technique with dynamic traffic in WDM optical networks,” *Optical Fiber Technology - Elsevier Science,* vol. 16, no. 1, pp. 50-54, January 2010.
2. Amit Wason, R.S. Kaler, “Lightpath rerouting algorithm to enhance blocking performance in all-optical WDM network without wavelength conversion,” *Optical Fiber Technology - Elsevier Science,* vol. 16, no. 3, pp. 146-150, June 2010.

In this chapter, the routing schemes for the survivable optical networks are taken into consideration, which is the second objective. In the first section, two routing algorithms have been proposed for dynamic provisioning of lightpath, which are very efficient in calculation and minimization of blocking probability. We have proposed two rerouting algorithms named Shortest Path Wavelength Rerouting (SPWRR) algorithm and Lightpath Rerouting Algorithm (LRRA) for dynamic traffic in WDM optical networks. In the second section, the simulation results and discussion has been covered and these algorithms have been implemented on realistic networks such as NSFnet. The results have shown that both these SPWRR and LRRA algorithm can improve blocking performance of the network. The proposed algorithms are low complexity algorithms. Hence, these algorithms have been applied to realistic network such as NSFnet for calculation and optimization of blocking probability of the given network. The results have also shown that lightpath rerouting algorithm can be implemented to huge networks for good blocking performance of the network

5.1. Rerouting Scheme for Survivable networks

Wavelength rerouting is a technique which is used to reduce the bandwidth loss caused by wavelength continuity constraint in wavelength routed network. Wavelength rerouting creates a wavelength-continuous route by shifting few existing lightpaths to new wavelengths without changing their route. It moves a few existing lightpaths to new wavelengths so as to create a wavelength-continuous route to satisfy a new connection request. Wavelength rerouting is applicable to networks with dynamic traffic demand. Further, it is also useful in case of failure of any network component. When a network component such as a node or link fails all lightpaths which currently use that node or link fail. To restore the service on these lightpaths new lightpath needs to be established between end nodes of failed lightpaths. In such a scenario, wavelength rerouting of unaffected lightpaths helps to restore the failed lightpaths. Wavelength rerouting basically has two components; the *rerouting operation (lightpath migration)* and the *rerouting algorithm* [24, 39]. The rerouting operation deals with migration of the lightpath. It is desirable that a rerouting operation incurs shorter disruption time and simplifies switching control at routing nodes. The rerouting algorithm determines lightpath that can be rerouted and selects few among them to create a wavelength-continuous route to satisfy a connection request. It is desirable that a rerouting algorithm should be simple, run in polynomial time and minimize the number of existing lightpath requests to be rerouted. We consider wavelength rerouting procedure as a possible approach to reduce network shortcoming arisen from wavelength continuity constraint.

5.2. SPWRR-Wavelength Rerouting Algorithm

We have proposed a shortest path wavelength rerouting algorithm which can be easily explained with figure (5.1). The key idea of this algorithm is to create a graph with crossover edges between any two nonadjacent nodes. The crossover edges are created only for lightpaths which could be rerouted to any other wavelength that is free on each link over considered path. Such lightpaths are also named returnable lightpaths. The objective of this algorithm is to minimize the weighted number of rerouted lightpaths in a network. The weighted number of rerouted lightpaths for a chosen path is number of existing returnable lightpaths intersected by that path. A weight associated to a lightpath represents the number of physical links on the path between end nodes. If a link is not used by any lightpath it is assigned a small value α. The cost of a path is defined as sum of weights associated with distinct lightpaths whose edges appear on a path plus number of free edges times value α. It is important to note that every intersecting lightpath is counted only once, independent of how many of its edges are used by considered paths.

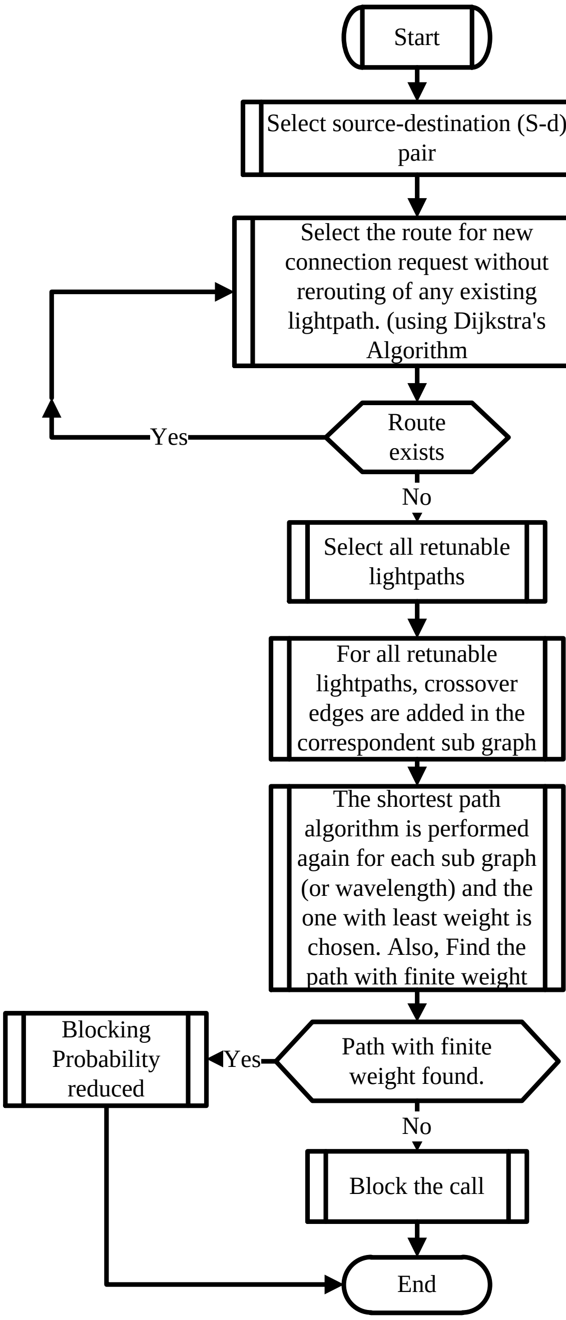


Figure 5.1: SPWRR Wavelength Rerouting Algorithm

The rerouting algorithm finds a path with minimum blocking between source and destination nodes. The algorithm works in two phases:

1. In the first phase, a route for a new connection requests is selected without rerouting of any existing lightpaths. If such a route does not exist the phase 2 is performed.
2. In second phase, a route for a new connection request is selected after rerouting some existing lightpaths to minimize the number of performed rerouting.

In phase 1, a conventional shortest path algorithm (such as Dijkstra's algorithm) is used to select the shortest path on each of the sub graphs (or wavelengths). Only free edges are considered while finding the shortest paths. Then the minimum weight path among them is chosen and it represents a path with the minimum number of physical hops. Phase 2 is performed only if phase 1 cannot give successful results. This phase consists of three steps. In first step, all re-tunable lightpaths are selected. In second step, for each re-tunable lightpath crossover edges are added in correspondent sub graph. Thus, the number of edges in obtained sub graphs could be increased. Finally in third step, the shortest path algorithm is performed again for each sub graph (or a wavelength) and one with least weight is chosen. The chosen path requires that the minimum weighted number of lightpaths should be rerouted. If no path with a finite weight can be found the connection request is rejected. The model used for calculation of blocking probability of wavelength convertible network for proposed algorithm is Model-I given by equation (3.7).

5.2.1. Simulation Results of SPWRR

To illustrate SPWRR algorithm, we have implemented this algorithm on NSFnet network topology (14-nodes, 21 links) given in figure (3.17). The established lightpaths in considered network are randomly chosen and are given in Table (5.1).

The results shown in figure (5.2) depict the variation of blocking probability with route length for NSFnet (network topology). We have assumed available number of wavelengths as four. The results show that blocking probability increases with the increase in route length. Since the route length can be controlled by the given SPWRR algorithm to a minimum value, hence blocking probability can be reduced to a minimum possible level. The blocking probability for given set of source-destination pairs can be given by table (5.2). The source-destination pairs are chosen randomly for given established lightpaths in the considered network. The results prove that blocking probability can be reduced effectively by using rerouting algorithm. Also, this rerouting algorithm is applicable for link restoration as is shown in table (5.2). If there is a link failure then this algorithm is helpful for the selection of available lightpath.

Table 5.1: Established lightpath routes, wavelengths and route lengths for SPWRR

Lightpath	Physical Route	Wavelength	Route Length
(5-6)	5-6	λ1	1
(6-10)	6-10	λ1	1
(1-3)	1-2-3	λ1	2
(5-8)	5-7-8	λ1	2
(5-11)	5-4-11	λ1	2
(11-13)	11-12-13	λ1	2
(1-13)	1-3-6-13	λ1	3
(1-14)	1-8-9-14	λ1	3
(4-5)	4-5	λ2	1
(2-3)	2-3	λ2	1
(1-9)	1-8-9	λ2	2
(6-9)	6-10-9	λ2	2
(9-11)	9-14-11	λ2	2
(1-11)	1-2-4-11	λ2	3
(1-5)	1-3-6-5	λ2	3
(6-11)	6-13-12-11	λ2	3
(6-8)	6-5-7-8	λ2	3
(1-2)	1-2	λ3	1
(1-7)	1-8-7	λ3	2
(1-6)	1-3-6	λ3	2

Table 5.2: Blocking probability for the given source destination pairs for SPWRR

Source-Destination pair	Physical lightpath selected by the algorithm	Route length	Blocking probability
1-7	1-8-7	2	0.004031
1-10	1-3-6-10	3	0.011966
2-11	2-4-11	2	0.004031
3-14	3-1-8-9-14	4	0.022222
1-14	1-8-9-14	3	0.011966
1-13	1-3-6-13	3	0.011966

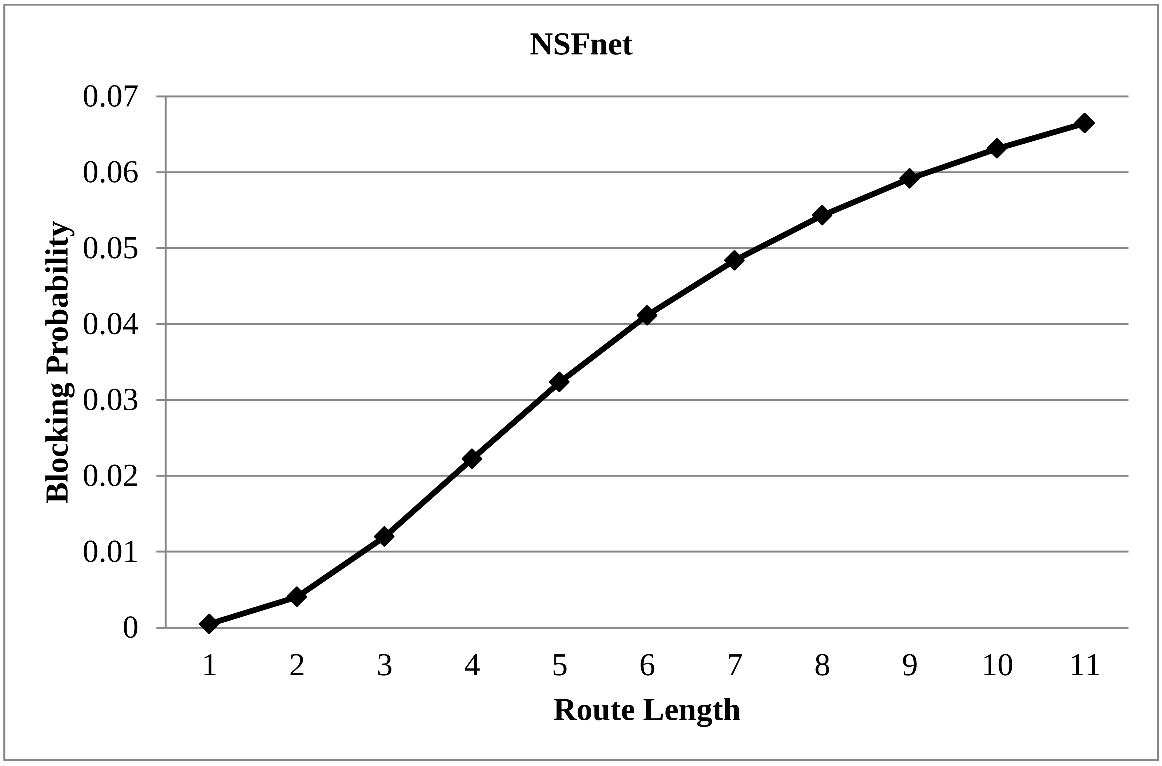


Figure 5.2: Blocking probability vs route length for NSFnet for SPWRR

5.3. Lightpath Rerouting Algorithm (LRRA)

A complete rerouting scheme generally has two components: rerouting algorithm and rerouting operation [36, 37]. A rerouting algorithm determines whether in order to accommodate a new connection, existing lightpaths or connections is to be rerouted and if one is rerouted which new paths is to be used. The rerouting operation decides the sequence of steps to be executed in networks to migrate rerouted lightpaths or connections to their new paths. The rerouting operation belongs to the function of control plane and largely determines rerouting disruption time [41]. For high-speed optical networks even a short disruption time may affect a large amount of traffic. Therefore, it is desirable that a rerouting scheme should incur the minimum disruption time.

5.3.1. Analytical Model

➢ *Given:*

- A physical topology $G_p = (V, E_p)$ consisting of a weighted bidirectional graph, where V is a set of network nodes and E_P is a set of physical links which connects the nodes. In this study nodes correspond to the network nodes and links corresponds to fiber between nodes. Links are assigned weights which may correspond to physical distance between nodes. We have assumed that all links have same weight 1 which corresponds to fiber hop distance. A network node i is assumed to be equipped with optical cross-connects or wavelength-routed switch.

- Number of wavelength channels carried by each fiber is Ch.
- N node WDM network.
- Fixed path routing policy is adopted for establishment of lightpath.
- R indicates the set of predetermined directed routes.
- r is the number of routes available where $r \in R$.
- l is the length of the route or number of links in the route or path selected.
- L_{sd}^{r} is the load on a route r.

For a network having l links having Ch channels (trunk or wavelengths) the arrivals are poisons while holding times are exponentially distributed with the unit mean. As stated by A. Birman in [89], for each route $r \in R$ the blocking probability for connections along route r can be given by equation (5.1).

$$B_{sd} = 1 - [1 - B(Ch, L_{sd}^{r})]^{l} \tag{5.1}$$

We can substitute the value of Erlang's loss formula $B(Ch, L_{sd}^{r})$ in equation (5.1) as:

$$B(Ch, L_{sd}^{r}) = \frac{\frac{(L_{sd}^{r})^{Ch}}{Ch!}}{\sum_{i=0}^{Ch} \frac{(L_{sd}^{r})^{i}}{i!}} \tag{5.2}$$

$$B_{sd} = 1 - \left[1 - \frac{\frac{(L_{sd}^{r})^{Ch}}{Ch!}}{\sum_{i=0}^{Ch} \frac{(L_{sd}^{r})^{i}}{i!}}\right]^{l} \tag{5.3}$$

Also, Load L_{sd}^{r} for a route r network having Ch channels, $N\lambda$ as the number of free wavelengths and l as route length can be given by equation (5.4) as:

$$L_{sd}^{r} = \frac{N\lambda}{l} \tag{5.4}$$

From equation (5.3) and equation (5.4) we can have blocking probability for connections along route *r* can be given equation (5.5) as:

$$B_{sd} = 1 - \left[1 - \frac{\frac{\left(\frac{N\lambda}{l}\right)^{Ch}}{Ch!}}{\sum_{i=0}^{Ch} \frac{\left(\frac{N\lambda}{l}\right)^{i}}{i!}}\right]^{l} \tag{5.5}$$

5.3.2. Rerouting Scheme

The LRRA is divided into three phases; rerouting detection, rerouting operation and blocking probability calculation. The basic idea of LRRA is to reroute some of the existing lightpaths so that new lightpaths can be established to carry an otherwise blocked connection. The lightpaths are established only for required connections and then connections are checked, if these connections are blocked then the new lightpath is established. While the new lightpath established after rerouting can be the only lightpath needed to carry a connection, it is also possible that new lightpath is one hop of path to carry a connection. The lightpath rerouting operation is executed when rerouting algorithm has decided which lightpaths are to be rerouted and which new paths are to be followed. As multiple lightpaths may be rerouted, we assume that they are computed by rerouting algorithm in such a way that they can be rerouted in parallel. This parallelism saves time needed to wait for completion of rerouting process. The basic rerouting algorithm can be easily understood by figure (5.3). Once rerouting operation finishes the routing algorithm can begin to establish a new connection.

In first phase of LRRA, rerouting is detected; this involves detection of lightpath which is to be rerouted. In the first step of this phase the LRRA determines s-d pair and lightpaths which are required for connection. The lightpaths are selected on the basis of the length of the route i.e. the shortest distance path is selected first. The lightpath is then checked for blocking on that lightpath. If the path is not blocked then same wavelengths are assigned to those paths and blocking probability of that lightpath is calculated. But if lightpath is blocked then it is checked for the blocked path. The paths are then checked whether it requires rerouting or not. In the second phase of this algorithm, the rerouting operation takes place. In this phase data transmission on all lightpaths is stopped and a new rerouted lightpath is established and after establishment of this new lightpath data transmission is again started. Same wavelengths are used by this lightpath which were used by old lightpaths. In the third phase of this algorithm blocking probability of this newly established path is calculated. If there is more number of lightpaths which are available then next shortest path is selected and whole process is repeated. The lightpath with the least blocking probability is selected for given s-d pair.

5.3.3. Results and Discussion of LRRA

To illustrate LRRA algorithm we have implemented this algorithm on NSFnet (network topology) given in figure (3.6). The established lightpaths in the considered network are randomly chosen and are shown in Table (5.3).

The results shown in figure (5.4) are plotted on semi logarithmic graph which shows the variation of blocking probability with the route length when LRRA algorithm is implemented on a realistic network topology (NSFnet). We have fixed the available number of wavelengths as 5 and the channel carried by fiber are taken as 10 and 12. The results prove that blocking probability decreases with the increase in the route length. Since route length can be controlled by the given LRRA algorithm the blocking probability can be reduced to a minimum possible level. Also, results prove that with increase in channel capacity blocking probability of the given system reduces to a large extent. The blocking probability for different sets of source-destination pairs is given by table (5.4). The source-destination pairs are chosen randomly for given established lightpaths in the considered network. The results show that blocking probability can be reduced effectively by using this rerouting algorithm. Also, this rerouting algorithm is applicable for the link restoration as is used in table (5.4). If there is a link failure then this algorithm is also helpful in the selection of available lightpath. Also, a combination of the model and proposed LRRA is also very useful in large networks as it is proved by results that blocking probability of network using this algorithm is reduced with the increase in route length. For the huge networks, the length of route will be large hence it will lead to a minimum blocking probability of the system and hence this algorithm can be useful for survivable WDM networks.

Table 5.3: Established lightpath routes, wavelengths and route lengths for LRRA

Lightpath	**Physical Route**	**Wavelength**	**Route Length**
(5-6)	5-6	λ1	1
(6-10)	6-10	λ1	1
(1-3)	1-2-3	λ1	2
(5-8)	5-7-8	λ1	2
(5-11)	5-4-11	λ1	2
(11-13)	11-12-13	λ1	2
(1-13)	1-3-6-13	λ1	3
(1-14)	1-8-9-14	λ1	3
(4-5)	4-5	λ2	1
(2-3)	2-3	λ2	1
(1-9)	1-8-9	λ2	2
(6-9)	6-10-9	λ2	2
(9-11)	9-14-11	λ2	2
(1-11)	1-2-4-11	λ2	3
(1-5)	1-3-6-5	λ2	3
(6-11)	6-13-12-11	λ2	3
(6-8)	6-5-7-8	λ2	3
(1-2)	1-2	λ3	1
(1-7)	1-8-7	λ3	2
(1-6)	1-3-6	λ3	2

Table 5.4: Blocking probability for the given source destination pairs for LRRA

Source-Destination pair	**Physical lightpath selected by the algorithm**	**Route length**	**Blocking probability using C=10**	**Blocking probability using C=12**
1-7	1-8-7	2	0.00043143	2.04297E-05
1-10	1-3-6-10	3	2.58237E-05	5.43433E-07
2-11	2-4-11	2	0.00043143	2.04297E-05
3-14	3-1-8-9-14	4	2.94123E-06	3.48157E-08
1-14	1-8-9-14	3	2.58237E-05	5.43433E-07
1-13	1-3-6-13	3	2.58237E-05	5.43433E-07

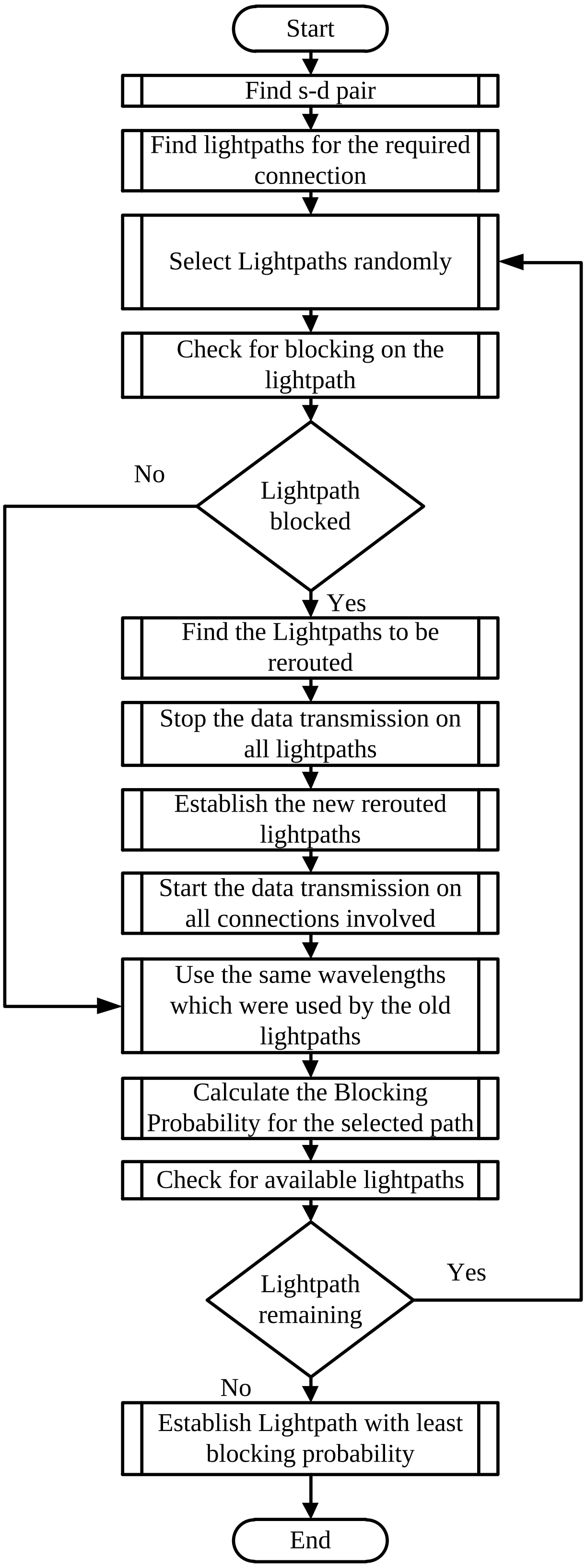


Figure 5.3: Lightpath Rerouting Algorithm

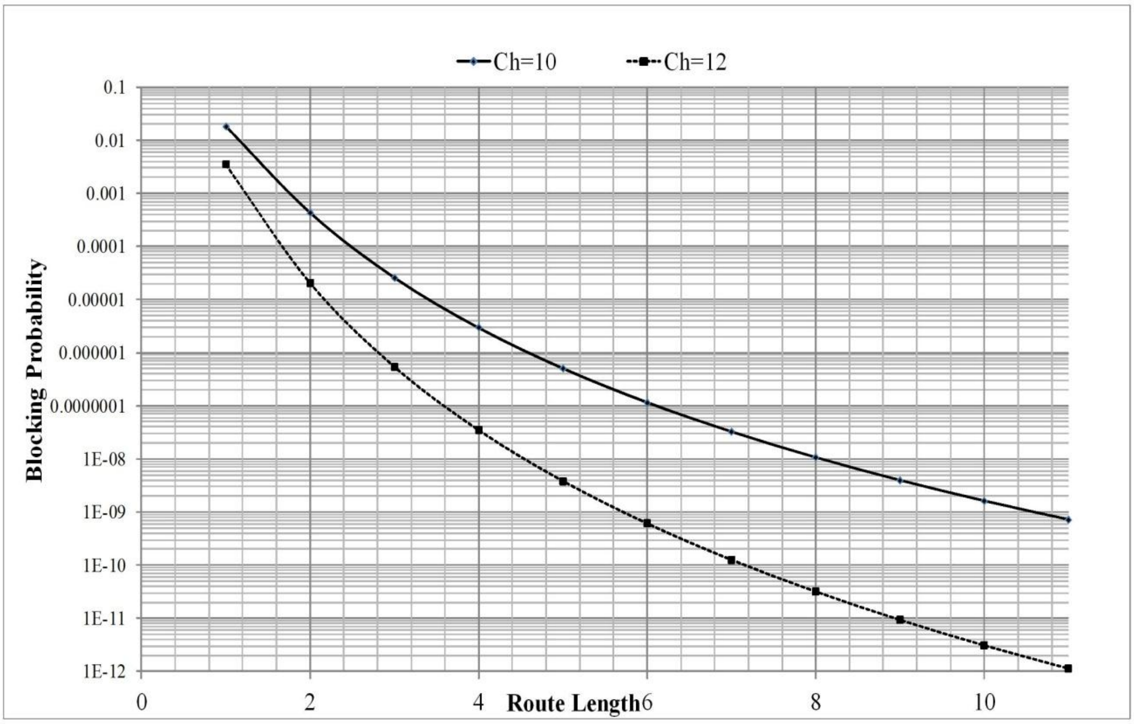


Figure 5.4: Blocking probability vs Route length for NSFnet for LRRA

5.4. Conclusions

In this chapter we have proposed two wavelength routing algorithms, results of these algorithms proved to be very effective. To improve the performance of all optical survivable WDM networks a technique based on wavelength rerouting has been applied. Wavelength rerouting approach as compared to the solution based on the wavelength conversion at network nodes is a viable and cost effective way to reduce considerably wavelength continuity constraint and consequently to improve network blocking performance. We have employed SPWRR and LRRA wavelength rerouting algorithm to investigate blocking performance and resource utilization of considered (NSFnet) WDM optical network topology. The key advantage of this algorithm as compared to routing and wavelength assignment algorithm is that it is very simple and requires less service disruption time. We have computed results for optical WDM network topology with dynamic traffic demands. As a result of the implementation of the proposed algorithms very few lightpaths were blocked in the considered WDM optical network.

CHAPTER 6

GROOMING AND RWA PROBLEM

Publications from chapter

1. Amit Wason, R.S. Kaler, “Routing and wavelength assignment in wavelength-routed all-optical WDM networks,” *Optik - International Journal for Light and Electron Optics - Elsevier Science*, Vol. 121, No. 16, pp. 1478-1486, September 2010.
2. Amit Wason, R. S. Kaler, “Fault-Tolerant Routing and Wavelength assignment algorithm for multiple link failures in Wavelength–Routed all-Optical WDM Networks,” *Optik -International Journal for Light and Electron Optics-Elsevier Science,* vol. 122, no. 2, pp. 110-113, January 2011
3. Amit Wason, R. S. Kaler, “Generic Routing and Wavelength Assignment Algorithm for a Wavelength-Routed WDM network,” *Optik –International Journal for Light and Electron Optics-Elsevier Science,* vol 122, no. 12, pp. 1100-1106, June 2011.
4. Amit Wason, R. S. Kaler, “Survivable Routing and Wavelength assignment algorithm for multiple link failures in Wavelength–Routed all-Optical WDM Networks,” *Optik –International Journal for Light and Electron Optics-Elsevier Science,* vol. 122, no. 12, pp. 1095-1099, June 2011.
5. Amit Wason, R. S. Kaler, “Genetic-II Routing and Wavelength Assignment Algorithm for a Wavelength-Routed WDM network,” *Optik –International Journal for Light and Electron Optics-Elsevier Science,* vol. 122, no. 12, pp. 1107-1112, June 2011.

In this chapter, we have investigated the third objective in order to develop and suggest new solutions for RWA while treating this problem as a single complete problem. In this chapter different solutions for RWA problem have been proposed. Some of the models proposed in chapter III of this thesis have been used for calculation and optimization of blocking probability. This chapter is divided into three sections; in the first section an algorithm named improved fixed-alternate RWA, has been proposed which is an improvement of fixed-alternated RWA. This solution to RWA problem is then implemented in realistic networks such as: NSFNET and EUPAN. In the second section the problem of enhancing multiple-fault restorability in path protected wavelength–routed all optical WDM networks has been discussed. Two solutions for this multiple link failure problem named; Fault-tolerant RWA and Survivable RWA have been proposed. The comparison of these algorithms has also been made with conventional algorithms. In the third section traffic grooming, routing and wavelength assignment problems have been taken as a single problem and two solutions are proposed namely Generic-I RWA and Generic-II RWA.

6.1. Proposed Improved Fixed-Alternate RWA

As discussed in literature, routing and wavelength assignment algorithm can be solved either as a single whole problem or it can be solved as two different problems. The proposed Improved Fixed-Alternate RWA (IFARWA) algorithm segregated RWA into two parts as Improved Fixed-Alternate Routing (IFRA) algorithm and Improved Fixed-Alternate Wavelength Assignment (IFAWA) algorithm. IFARWA is the combination of proposed improved fixed-alternate routing algorithm and improved fixed-alternate wavelength assignment algorithm. The mathematical model used is *Model-I* which can be given by equation (3.7).

6.1.1. Improved Fixed Alternate Routing Algorithm

The routing algorithm proposed is an improvement of fixed-alternate routing algorithm. This algorithm can easily be illustrated with the help of figure (6.1). For every node pair *p*, a set of K candidate routes (more than one) is provided. These routes are computed offline. The set of candidate routes provided for a node pair is a subset of all possible routes for the node-pair. When a connection request arrives for a pair *p*, one of the candidate routes is searched in a fixed order and first candidate route with a defined cost is selected. The hop count and delay are normally used as cost metric. If no route can be found with a fixed cost i.e. no wavelength is free on any of the candidate route then a wavelength selection algorithm can be used to choose one of them. Although this algorithm is slightly more complex than fixed routing algorithm, it also has an advantage of simplicity and shorter connection setup time. If *H* is the length of the longest candidate route for any node pair then this algorithm runs in *O (KHW)* time units. It has better performance than the FR algorithm as it has choice among more than one candidate routes for any s-d pairs of nodes. However, the candidate route provided for a node pair may include all possible routes.

```
Start
Calculate every node pair (p);
For (1<p1<p)
        {
                Calculate K routes;             for K >1;
        }
Calculate blocking probability;
for (blocking probability to be minimum)
        {
                While (blocking probability $\neq 1$)
                        {
                        select a route K1;      where K1 belongs to K;
                        calculate blocking probability;
                        if (blocking probability = 1)
                                {route blocked}
                        }
        }
End
```

Figure 6.1: Improved fixed alternate routing algorithm

6.1.2. Improved Fixed Alternate Wavelength Assignment Technique

A wavelength assignment technique has been proposed which is based on mathematical model (Model-I). We can calculate blocking probability by using this model. For a given routing algorithm the number of wavelengths which are required for minimizing blocking probability can be calculated by using this proposed algorithm. Further, the number of wavelengths calculated can be fixed to the number of wavelengths which are available in the network resulting in the minimization of blocking probability. This algorithm can be easily explained with the help of figure (6.2).

6.1.3. Simulation Results of IFARWA

We have considered a network without wavelength conversion. The total blocking probability of the network depends upon blocking probability caused by insufficient wavelength, P_{BW}^{r}. This blocking probability can be reduced and fixed to a particular level by fixing the total number of wavelengths hence blocking probability of the network depends only on the number of free wavelengths and the length of the route. We have fixed the value of blocking probability, P_{BW}^{r} to 0.1 and varied the number of free wavelengths, $N\lambda$ and length of route and then calculated total blocking probability of network.

```
Start
for (all routes)
            {
            calculate blocking probability;
            }
select source destination (s-d) pair;
select route K1;
calculate the number of wavelengths;
assign wavelength to the route;
end
```

Figure 6.2: IFAWA Technique

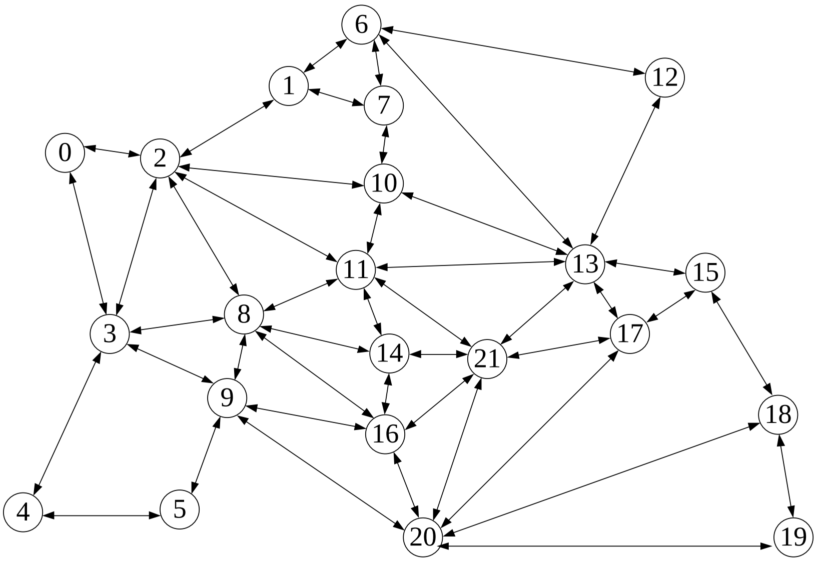


Figure 6.3: EUPAN (Network topology)

Table (6.1) shows blocking probability of the network at a particular length of route l and having a number of free wavelengths, $N\lambda$. It is clear from the table that blocking probability increases with increase in route length and decreases with the number of free wavelengths present on the path. This IFARWA has been applied to different network topologies such as NSFNet and EUPAN which are shown in figure (3.2) and figure (6.3) respectively.

For NSFNet, we have assumed node 1 as source node and node 14 as destination node. There are a number of possible routes from source to destination but maximum available length of route can be 10. The blocking probability for NSFNet is shown in Table (6.2). The simulation results for NSFNet are shown in figure (6.4) and figure (6.5).

Table 6.1: Blocking probability calculation for IFARWA

Route Length	**Number of free Wavelengths**							
L	**$N\lambda=1$**	**$N\lambda=2$**	**$N\lambda=3$**	**$N\lambda=4$**	**$N\lambda=5$**	**$N\lambda=10$**	**$N\lambda=50$**	**$N\lambda=100$**
1	0.02222	0.00403	0.00118	0.00048	0.00025	4.5E-05	1.2E-05	1.1E-05
5	0.08166	0.06314	0.04614	0.03233	0.02222	0.00403	4.5E-05	1.8E-05
10	0.09091	0.08165	0.07234	0.06315	0.05433	0.02222	0.00025	4.5E-05
15	0.09396	0.08784	0.08166	0.07544	0.06925	0.04113	0.00085	0.00011
20	0.09548	0.09091	0.08630	0.08166	0.07700	0.05433	0.00207	0.00025
25	0.09639	0.09274	0.08907	0.08537	0.08166	0.06315	0.00403	0.00048
30	0.09699	0.09396	0.09091	0.08784	0.08476	0.06925	0.00674	0.00085
35	0.09742	0.09482	0.09222	0.08960	0.08696	0.07367	0.01010	0.00137
40	0.09774	0.09548	0.09320	0.09091	0.08861	0.07700	0.01392	0.00207
45	0.09800	0.09598	0.09396	0.09193	0.08989	0.07959	0.01802	0.00295
50	0.09819	0.09639	0.09457	0.09274	0.09091	0.08166	0.02222	0.00403
55	0.09836	0.09671	0.09506	0.09341	0.09174	0.08335	0.02638	0.00530
60	0.09850	0.09699	0.09548	0.09396	0.09244	0.08476	0.03040	0.00674
65	0.09861	0.09722	0.09582	0.09443	0.09302	0.08594	0.03421	0.00835
70	0.09871	0.09742	0.09613	0.09483	0.09352	0.08696	0.03780	0.01010
75	0.09880	0.09759	0.09639	0.09517	0.09396	0.08784	0.04113	0.01197
80	0.09887	0.09774	0.09661	0.09548	0.09434	0.08861	0.04422	0.01392
85	0.09894	0.09788	0.09681	0.09574	0.09467	0.08929	0.04706	0.01595
90	0.09900	0.09800	0.09699	0.09598	0.09497	0.08989	0.04969	0.01802
95	0.09905	0.09810	0.09715	0.09619	0.09524	0.09043	0.05210	0.02012
100	0.09910	0.09820	0.09729	0.09639	0.09548	0.09548	0.05433	0.02222

Table 6.2: Implementation of IFARWA on NSFnet

Route Length	**Number of free Wavelengths**						
L	**Nλ=1**	**Nλ=2**	**Nλ=3**	**Nλ=4**	**Nλ=5**	**Nλ=6**	**Nλ=7**
1	0.022222	0.004031	0.001178	0.000484	0.000248	0.000148	9.90E-05
2	0.054329	0.022222	0.00892	0.004031	0.002067	0.001178	0.00073
3	0.06925	0.041131	0.022222	0.011966	0.006744	0.004031	0.00255
4	0.076998	0.054329	0.035436	0.022222	0.013925	0.00892	0.005897
5	0.081659	0.063147	0.046141	0.032334	0.022222	0.01527	0.010623
6	0.084757	0.06925	0.054329	0.041131	0.030398	0.022222	0.016246
7	0.086962	0.07367	0.060577	0.048404	0.037797	0.029079	0.022222
8	0.08861	0.076998	0.06542	0.054329	0.044217	0.035436	0.028123
9	0.089889	0.079589	0.06925	0.059166	0.049688	0.041131	0.033684
10	0.09091	0.081659	0.072341	0.063147	0.054329	0.046141	0.038775

It is clear from figure (6.4) and Table (6.2) that the blocking probability is minimum with the $N\lambda = 7$ but we can achieve a compromise between route length and number of wavelengths using proposed algorithms which has been explained in Table (6.3), Table (6.4), figure (6.5) and figure (6.6).

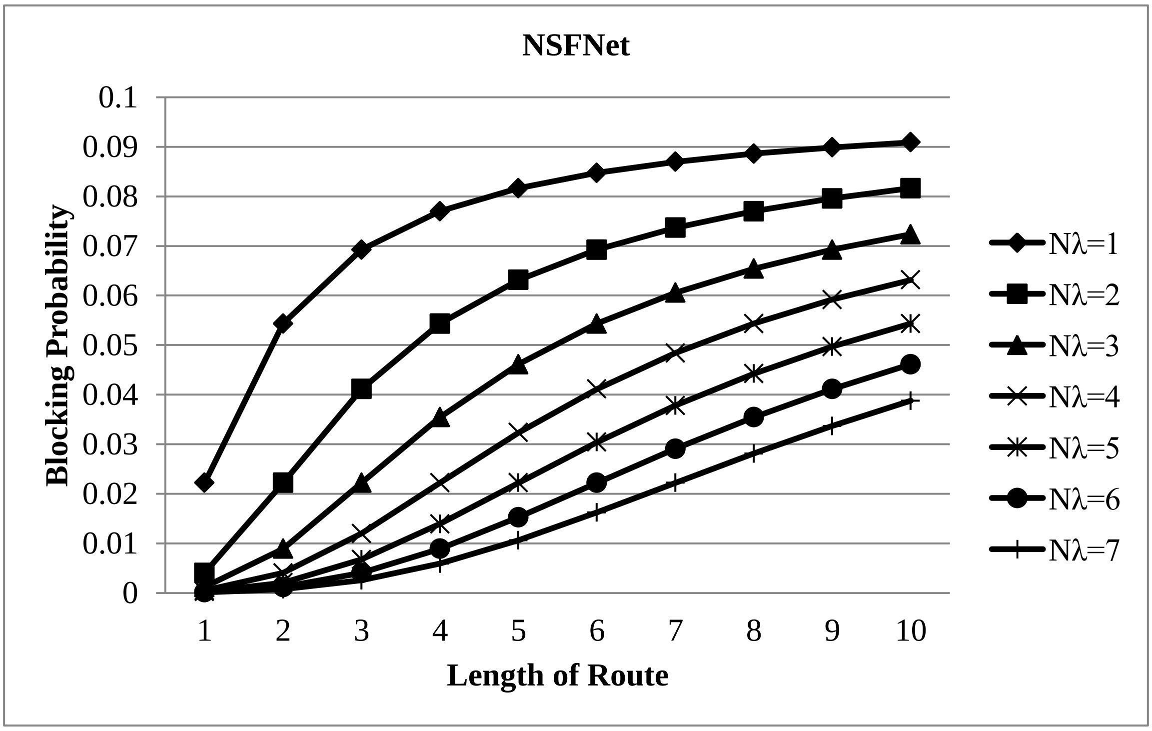


Figure 6.4: Blocking Probability vs. Length of the route for IFARWA on NSFnet

Table 6.3: Implementation of IFARWA

S. No.	Source-Destination Pair	Route	Wavelengths Required	Blocking Probability
1	1-14	1-3-6-14	3	0.022222
2	1-14	1-2-3-6-14	3	0.022222
3	1-14	1-2-4-5-6-14	4	0.022222
4	1-14	1-2-4-11-12-14	4	0.022222
5	1-14	1-8-7-5-6-14	4	0.022222
6	1-14	1-8-10-9-6-14	5	0.022222
7	1-14	1-8-7-5-4-11-12-14	7	0.022222

The improved fixed alternate routing and wavelength assignment technique is implemented on different network topologies. The route calculation for NSFNet is given in table (6.3). In this table we have fixed blocking probability for different routes for a particular source-destination pairs (1-14) and calculated the number of wavelength required for the network. The number of wavelengths required can also be fixed to a particular value for different routes for a particular source-destination pair and then blocking probability is calculated using proposed model. The results have been shown in table (6.4) and figure (6.7).

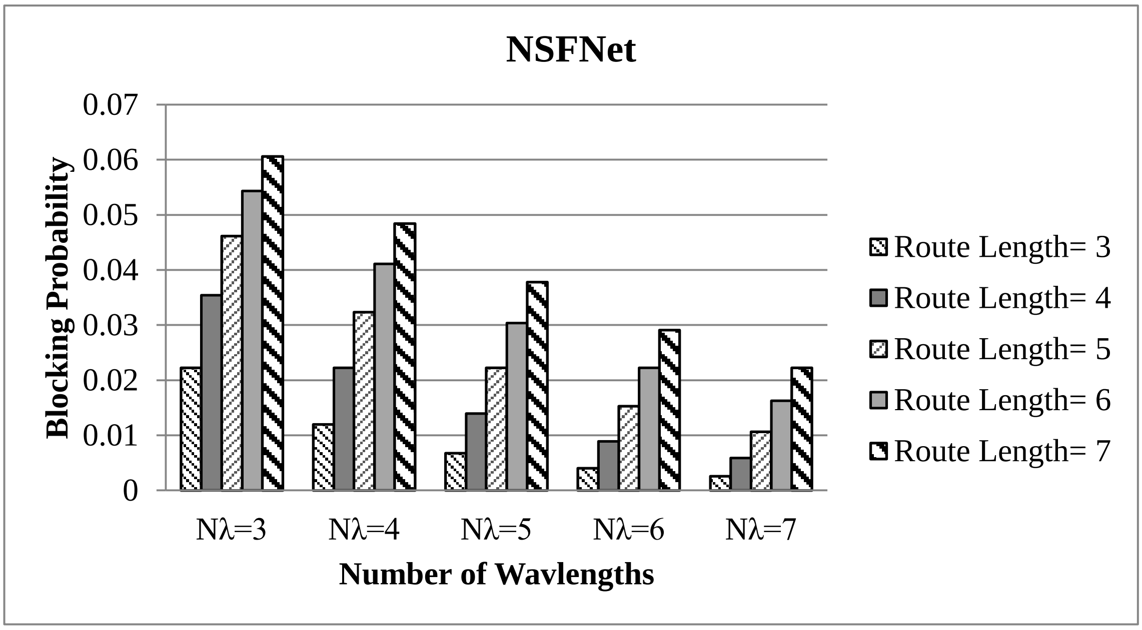


Figure 6.5: Blocking Probability vs. Number of free wavelengths for IFARWA on NSFNet

Further IFARWA has also been implemented on EUPAN Network topology. Implementation of IFARWA on EUPAN Network topology has been shown in table (6.5).

Table 6.4: Implementation of IFARWA technique on NSFnet for fixed number of wavelength.

S. No.	Source-Destination Pair	Route	Wavelengths Required	Blocking Probability
1	1-14	1-3-6-14	3	0.022222
2	1-14	1-2-3-6-14	3	0.022222
3	1-14	1-2-4-5-6-14	3	0.035436
4	1-14	1-2-4-11-12-14	3	0.035436
5	1-14	1-8-7-5-6-14	3	0.035436
6	1-14	1-8-10-9-6-14	3	0.046141
7	1-14	1-8-7-5-4-11-12-14	3	0.060577

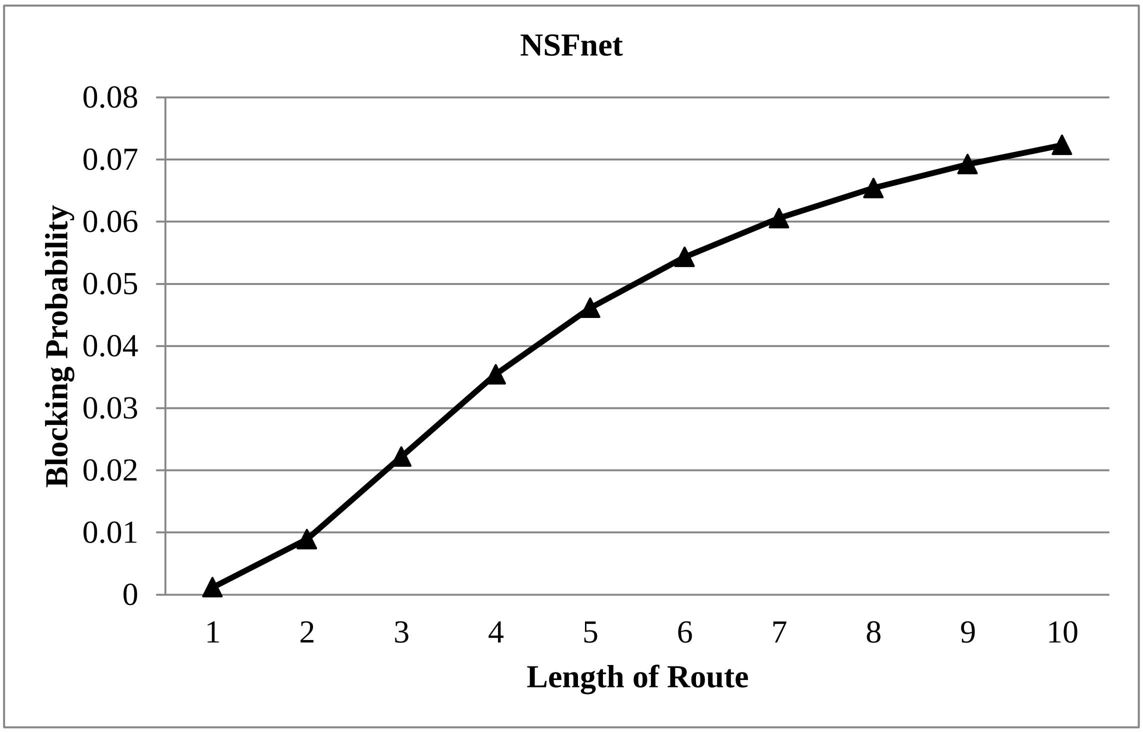


Figure 6.6: Implementation of IFARWA on NSFnet

In case of EUPAN network topology, node 0 is assumed to be as source node and node 21 as destination node. There are a number of routes from source to destination but maximum length of route available can be 21. The blocking probability for EUPAN Network topology has been shown in table (6.5) and simulation results in figure (6.7).

The variation of blocking probability of EUPAN network is shown in table (6.5) and figure (6.8). The figure (6.8) shows the complete variation of blocking probability with respect to the length of route for EUPAN Network. We have further implemented the proposed routing algorithm and wavelength assignment technique for the improvement of results. The implementation of IFARWA proposed algorithms is discussed in table (6.5), figure (6.8) and figure (6.9).

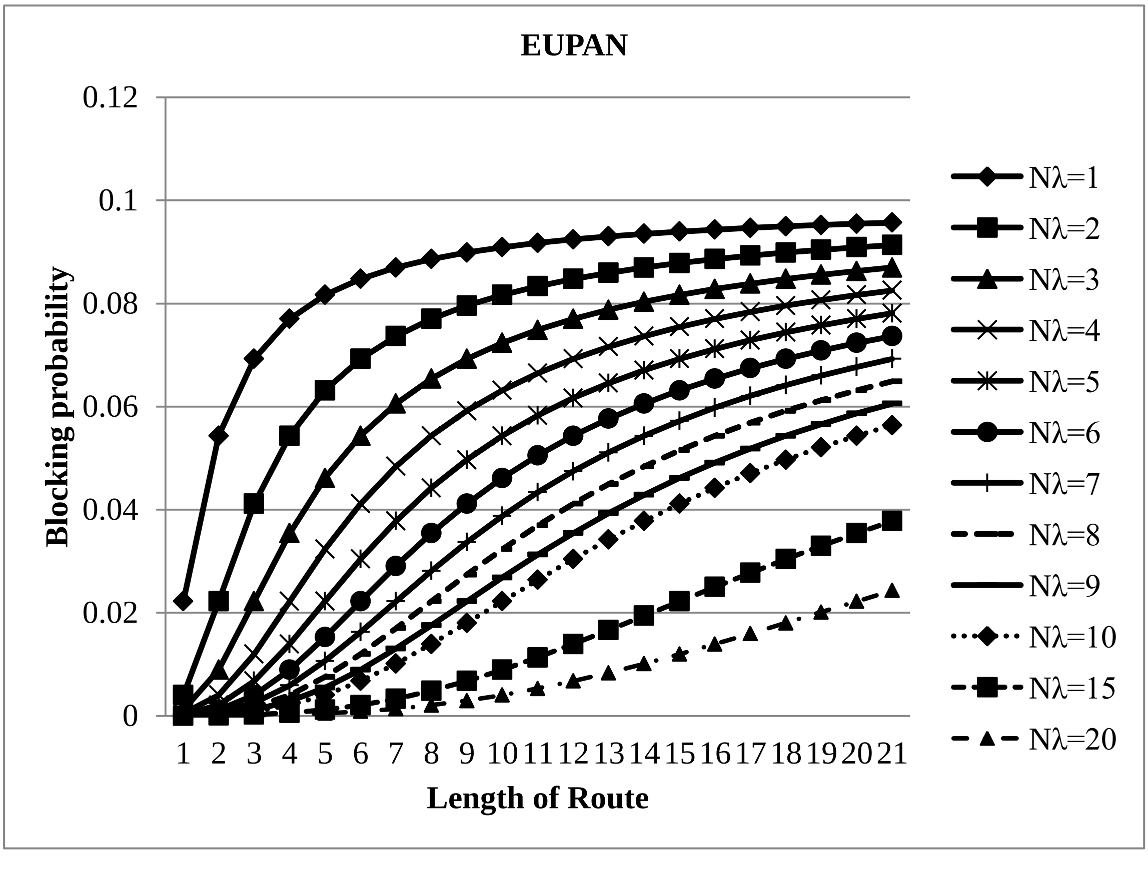


Figure 6.7: Blocking Probability vs. Length of route for IFARWA on EUPAN

6.2. Proposed Fault-Tolerant RWA

Fault-Tolerant RWA (FTRWA) Algorithm can be stated as a combination of proposed fault-tolerant routing algorithm and fault-tolerant wavelength assignment algorithm. The mathematical model used for this algorithm is *Model-I* given by equation (3.7).

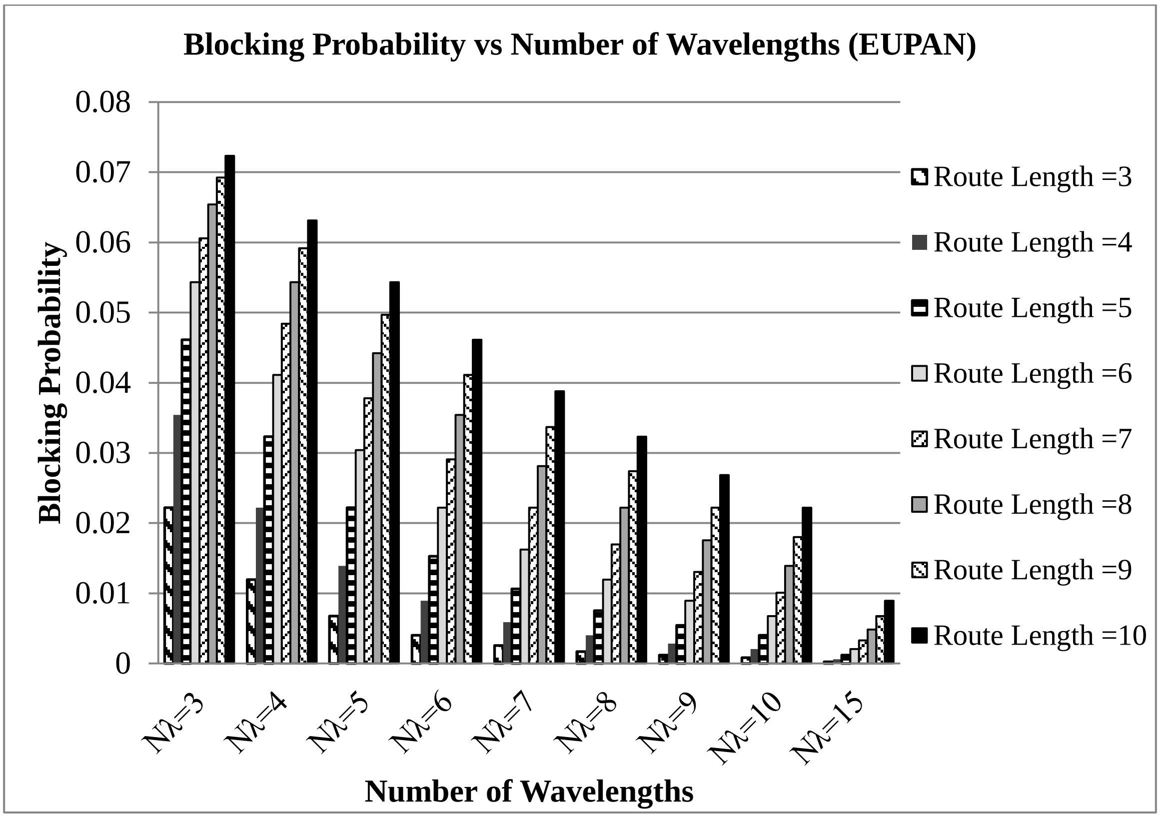


Figure 6.8: Blocking Probability vs. Number of free wavelengths for IFARWA on EUPAN

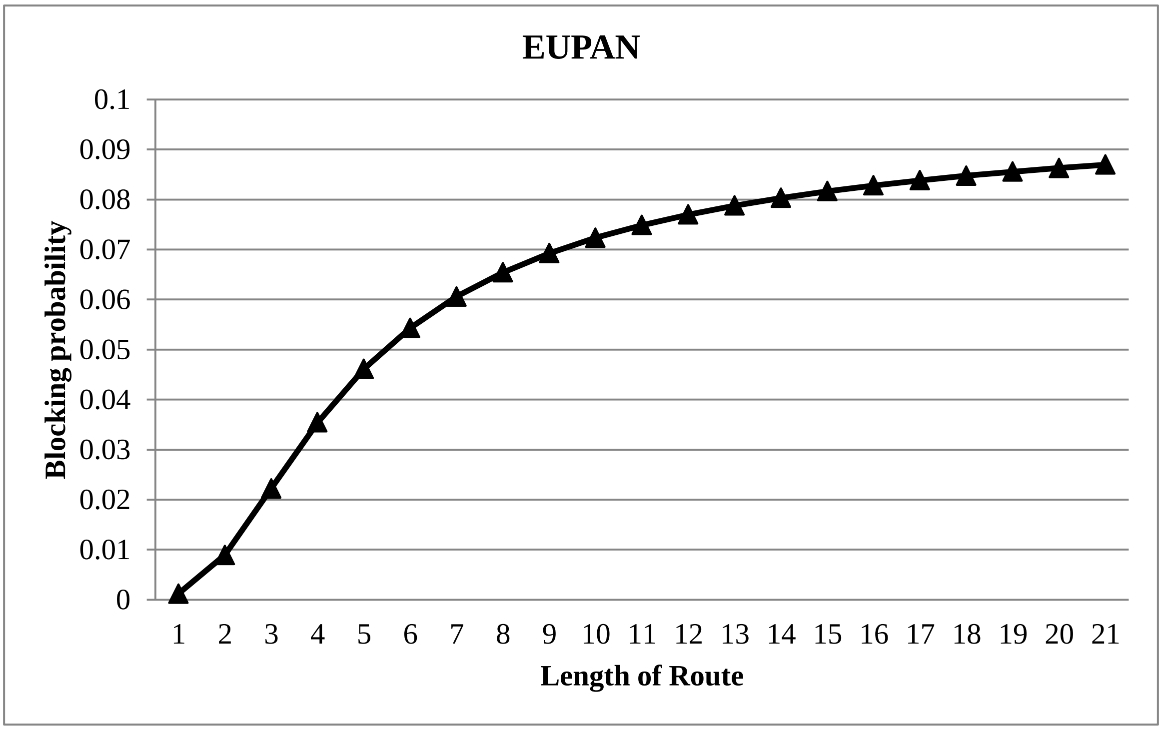


Figure 6.9: Implementation of IFARWA on EUPAN

Table 6.5: Implementation of IFARWA on EUPAN Network.

S. No.	**Source-Destination Pair**	**Route**	**Wavelengths Required**	**Blocking Probability**
1	0-21	0-2-11-21	3	0.022222
2	0-21	0-2-11-14-21	4	0.022222
3	0-21	0-2-11-13-21	4	0.022222
4	0-21	0-2-10-11-21	4	0.022222
5	0-21	0-2-10-13-21	4	0.022222
6	0-21	0-2-8-11-21	4	0.022222
7	0-21	0-2-8-14-21	4	0.022222
8	0-21	0-3-8-11-21	4	0.022222
9	0-21	0-3-8-14-21	4	0.022222
10	0-21	0-3-2-11-21	4	0.022222
12	0-21	0-2-11-14-21	3	0.035436
13	0-21	0-2-11-13-21	3	0.035436
14	0-21	0-2-10-11-21	3	0.035436
15	0-21	0-2-10-13-21	3	0.035436
16	0-21	0-2-8-11-21	3	0.035436
17	0-21	0-2-8-14-21	3	0.035436
18	0-21	0-3-8-11-21	3	0.035436
19	0-21	0-3-8-14-21	3	0.035436
20	0-21	0-3-2-11-21	3	0.035436

6.2.1. Proposed Fault-Tolerant Routing Algorithm

We have proposed fault-tolerant routing algorithm which has been illustrated clearly by figure (6.10). According to this algorithm first of all source-destination pair is checked and then all possible paths for that source-destination path are calculated. These paths are then arranged in order of preference depending on the path length. The shortest path is fixed as the first preference and every path is then assigned a preference. The link failures are then checked, if there is no failure on shortest path then the path is established. If there is a failure on the path then that path is dropped and next path preference is checked for failure. This process is repeated until call is established.

```
Fault Tolerant Routing Algorithm

1.  Begin
2.  Check for the source-destination pairs.
3.  Calculate every possible path between s-d pair.
4.  Arrange in order of preference. (shortest path first)
5.  Check for the link failure (if any)
6.  Try for the shortest path, if there is link failure (set call temp block)
    in the shortest path then try the next preferred path.
7.  Repeat step-5 until call temp unblocks.
8.  End.
```

Figure 6.10: Fault tolerant routing algorithm

6.2.2. Fault-Tolerant Wavelength Assignment Algorithm (FTWA)

This proposed wavelength assignment algorithm can be easily explained by figure (6.11). According to this algorithm no wavelength is assigned to any lightpath until it has any fault. This algorithm checks for the establishment of fault free path. When the path is established a particular wavelength is assigned to the established path. This will lead to proper utilization of wavelength.

```
Fault Tolerant Wavelength Assignment Algorithm

1.  Begin
2.  Do not assign any wavelength to any path
3.  Check for the establishment of fault free path
4.  When path established, assign wavelength to that path
5.  End
```

Figure 6.11: Fault-tolerant wavelength assignment algorithm

6.2.3. Simulation Results of FTRWA

We have considered a network without wavelength conversion. The proposed algorithms can be implemented on any network topology such as NSFnet topology having 14 nodes and 19 links as shown in figure (3.2). The assumption has been made that at least one of the links 1-2, 1-3 or 1-8 is fault free. For NSFNet we assume node 1 as source node and node 14 as destination node. There are a number of routes from source to destination. All possible paths along their route length are calculated using proposed routing algorithm and are tabled as shown in table (6.6) in order of preference.

Now with the use of wavelength assignment algorithms the blocking probability caused by insufficient wavelength i.e. P_{BW}^{r} can be reduced to a very small value up to 0.05. The figure (6.12) show blocking probability distribution with respect to the route length and the number of wavelengths. The minimum number of wavelengths is used in the network for better performance of the network. The blocking probability variation of proposed FTRWA with respect to load per node (in Erlangs) is given by figure (6.13) whereas when dealing with blocking probability variation for first-fit and best fit routing algorithm as depicted by Mahesh Sivakumar *et. al.* in [114] is given by figure (6.14). Thus, a comparison can be made from figure (6.13) and figure (6.14) that the proposed FTRWA algorithm work better than the conventional algorithms, even at the larger load. The performance of the proposed algorithm increases whereas that of conventional algorithms decreases when the load applied is increased.

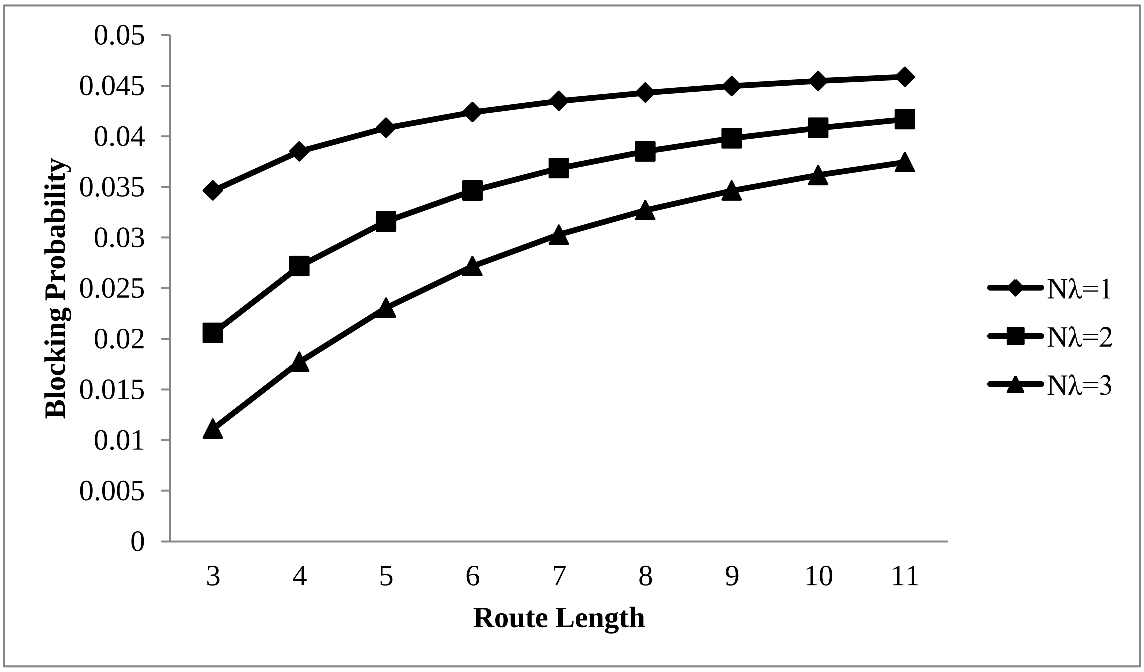


Figure 6.12: Blocking probability of proposed FTRWA algorithm, as a function of route length, with 30 wavelengths per link for NSFnet (14 nodes and 23 links)

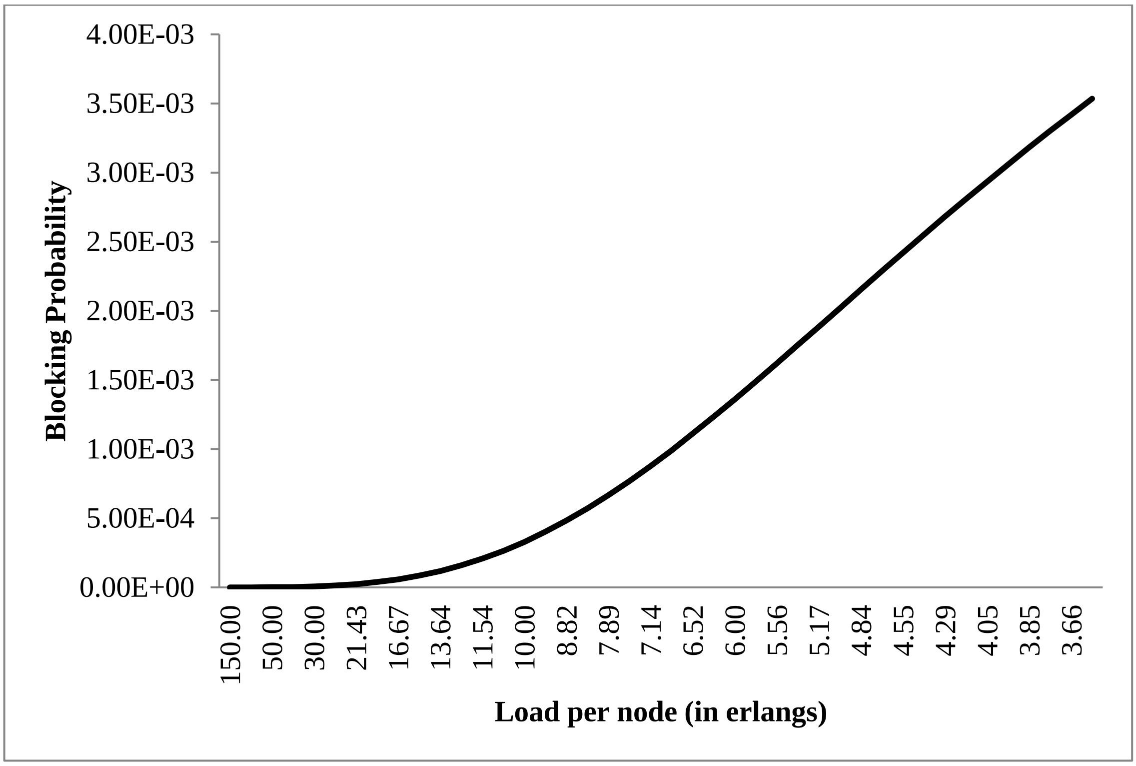


Figure 6.13: Blocking probability of proposed FTRWA algorithm as a function of load, with 30 wavelengths per link for NSFnet (14 nodes and 23 links)

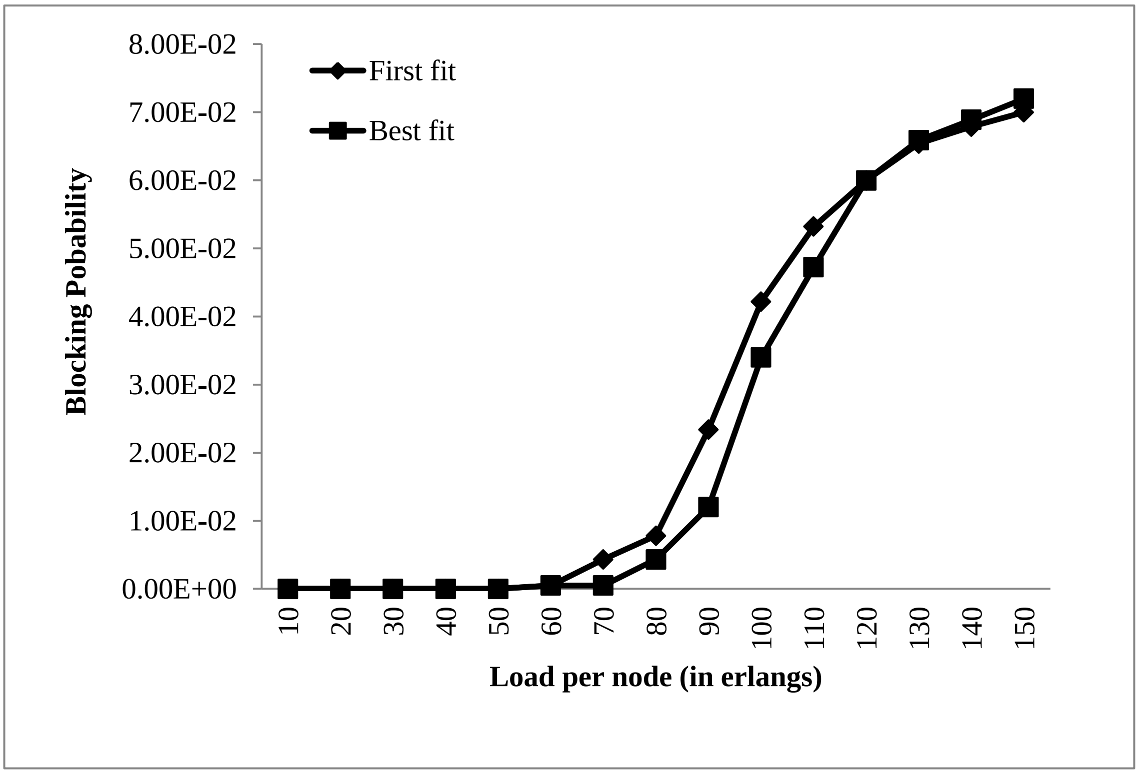


Figure 6.14: Blocking probability of best-fit and first-fit routing algorithm as a function of load, with 30 wavelengths per link for NSFnet, with14 nodes and 23 links. [114]

Table 6.6: Possible route calculation using FTRWA Algorithm.

Order of preference	**Source-Destination Pair**	**Route**	**Route Length**
1	1-14	1-3-6-14	3
2	1-14	1-2-3-6-14	4
3	1-14	1-2-4-5-6-14	5
4	1-14	1-2-4-11-12-14	5
5	1-14	1-8-7-5-6-14	5
6	1-14	1-8-10-9-6-14	5
7	1-14	1-8-10-13-11-12-14	6
8	1-14	1-8-7-5-4-11-12-14	7
9	1-14	1-3-6-5-4-11-12-14	7
10	1-14	1-2-3-6-5-4-11-12-14	8
11	1-14	1-2-4-11-13-10-9-6-14	8
12	1-14	1-8-10-13-11-4-5-6-14	8
13	1-14	1-2-4-5-7-8-10-9-6-14	9
14	1-14	1-8-10-9-6-5-4-11-12-14	9
15	1-14	1-8-10-13-11-4-2-3-6-14	9
16	1-14	1-3-6-5-7-8-10-13-11-12-14	10
17	1-14	1-2-4-5-7-8-10-13-11-12-14	10
18	1-14	1-2-4-11-13-10-8-7-5-6-14	10
19	1-14	1-8-7-5-4-11-13-10-9-6-14	10
20	1-14	1-8-7-5-6-9-10-13-16-12-14	10
21	1-14	1-2-3-6-5-7-8-10-13-11-12-14	11

6.3. Proposed Survivable RWA Algorithm

Survivable RWA (SRWA) Algorithm can be stated as a combination of proposed survivable routing and survivable wavelength assignment algorithm. The mathematical model used for this proposed algorithm is *Model-IV* which is given by equation (3.21).

6.3.1. Proposed Survivable Routing Algorithm

Survivable routing algorithm can be easily illustrated by figure (6.15). According to this algorithm first of all source-destination pair is checked and then every possible paths for that source-destination pair are calculated. These paths are then arranged in order of preference depending upon the path length, shortest path is fixed as the first preference and every path is then assigned a preference. The link failures are then checked; if there is no failure on the shortest path then the path is established. If there is a link failure then the path is dropped and next path preference is checked. This process is repeated until the call is established.

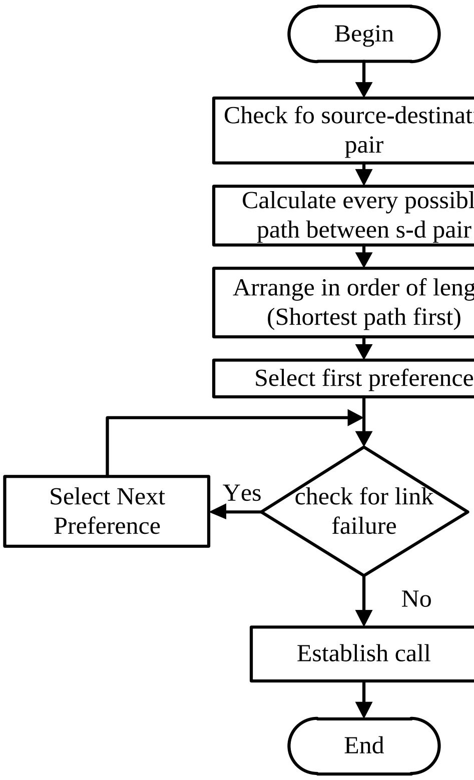


Figure 6.15: Survivable routing algorithm

6.3.2. Proposed Survivable Wavelength Assignment Algorithm

This proposed wavelength assignment algorithm can easily be explained by figure (6.16). According to this algorithm no wavelength is assigned to any lightpath until it has any fault. This algorithm first check for availability of wavelengths and then wavelengths are arranged in an order and a number *N* is assigned to every wavelength. The call is then checked for the establishment of fault free path. If this call is not established the algorithm will wait until it is established and if call is established the algorithm assigns a wavelength with lowest number *N*. This will lead to proper utilization of wavelength and better performance of the network.

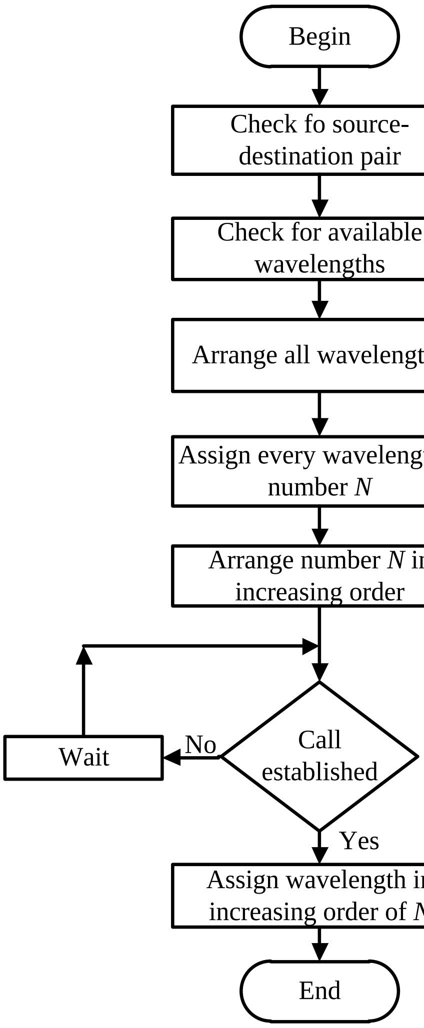


Figure 6.16: Survivable wavelength assignment algorithm

6.3.3. Simulation Results of SRWA

We have considered a network without wavelength conversion. Further, proposed algorithms were implemented on NSFnet network topology shown in figure (3.17). The assumption has been made that at least one of the links 1-2, 1-3 or 1-8 is fault free. For NSFnet we have assumed node 1 as source node and node 14 as destination node. There are a number of routes from source to destination. All possible paths along with their route length are calculated using this proposed routing algorithm and are tabulated as shown in table (6.7) in order of preference.

Blocking probability of proposed algorithm for different paths of NSFnet (14 nodes and 21 links) have been shown in figure (6.17) in which 1-14 pair is taken as s-d pair. The figure (6.18) shows blocking probability of this proposed survivable routing and wavelength assignment algorithm as a function of load. The number of channels is taken as 10 for NSFnet (14 nodes and 21 links) and blocking probability is checked for different values of load per node. The results have shown that blocking probability of proposed survivable routing and wavelength assignment algorithms increases with increase in load on a node but it is considerably very small (of the value of 0.8% for the load of 50 Erlangs per node). Hence, this routing and wavelength assignment algorithm can be implemented on a network where load on a node is high. Also as depicted by the results blocking probability is very small at higher load.

Table 6.7: Possible route calculation using SRWA algorithm

Order of preference	**Source-Destination Pair**	**Route**	**Route Length**
1	1-14	1-3-6-14	3
2	1-14	1-2-3-6-14	4
3	1-14	1-2-4-5-6-14	5
4	1-14	1-2-4-11-12-14	5
5	1-14	1-8-7-5-6-14	5
6	1-14	1-8-10-9-6-14	5
7	1-14	1-8-10-13-11-12-14	6
8	1-14	1-8-7-5-4-11-12-14	7
9	1-14	1-3-6-5-4-11-12-14	7
10	1-14	1-2-3-6-5-4-11-12-14	8
11	1-14	1-2-4-11-13-10-9-6-14	8
12	1-14	1-8-10-13-11-4-5-6-14	8
13	1-14	1-2-4-5-7-8-10-9-6-14	9
14	1-14	1-8-10-9-6-5-4-11-12-14	9
15	1-14	1-8-10-13-11-4-2-3-6-14	9
16	1-14	1-3-6-5-7-8-10-13-11-12-14	10
17	1-14	1-2-4-5-7-8-10-13-11-12-14	10
18	1-14	1-2-4-11-13-10-8-7-5-6-14	10
19	1-14	1-8-7-5-4-11-13-10-9-6-14	10
20	1-14	1-8-7-5-6-9-10-13-16-12-14	10
21	1-14	1-2-3-6-5-7-8-10-13-11-12-14	11

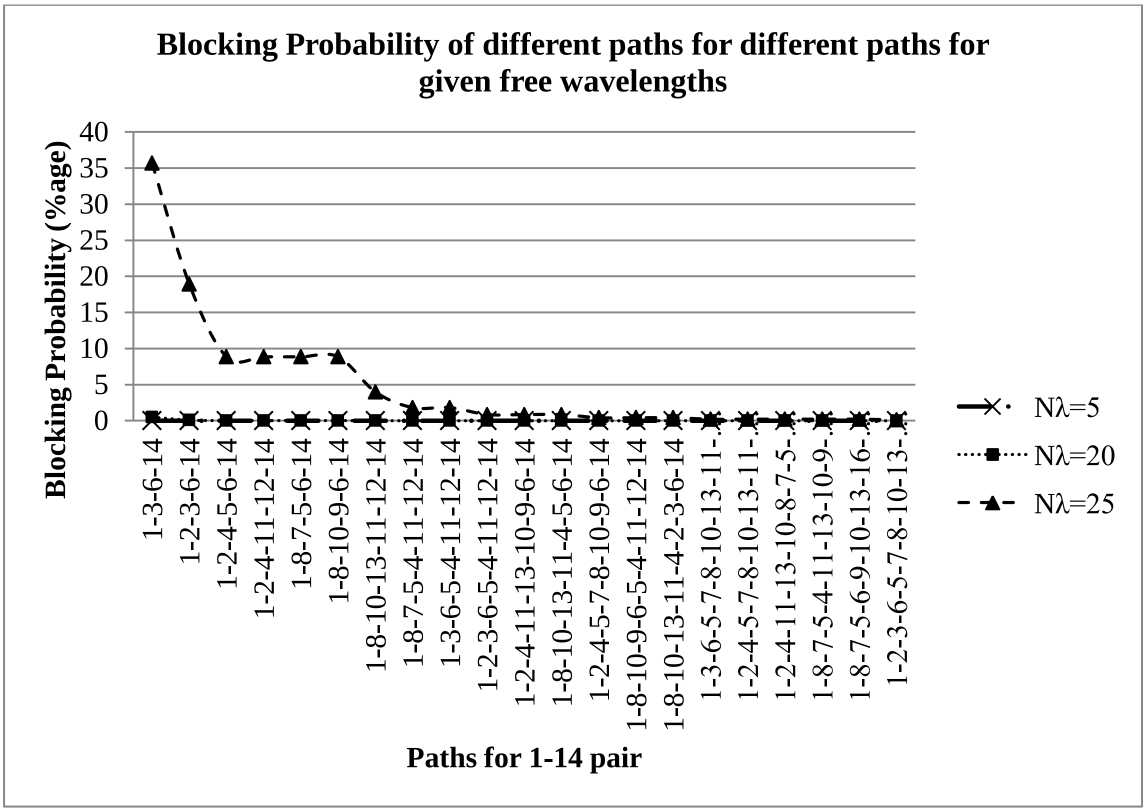


Figure 6.17: Blocking Probability of SRWA algorithm for different paths for 1-14 node pair for free wavelengths on NSFnet (14 nodes and 21 links)

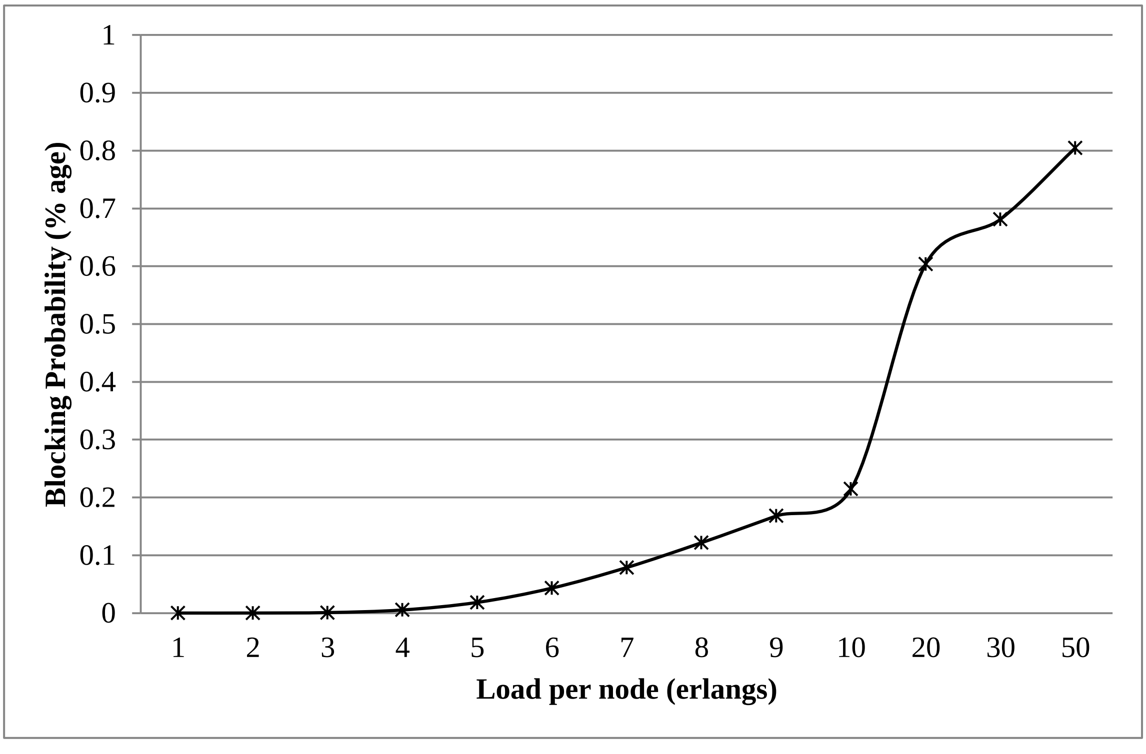


Figure 6.18: Blocking probability of proposed SRWA algorithm as a function of load, with 10 channels for NSFnet (14 nodes and 21 links).

6.4. Proposed Generic RWA Algorithms

We have proposed two Generic RWA Algorithms (GRWA-I and GRWA-II) which deal with problem of traffic grooming, routing and wavelength assignment as a single complete problem. These algorithms deal with these problems without treating them as different problems.

6.4.1. Problem Definition

Problem Statement

The problem can be formally defined as follows.

- *Given:*
- A physical topology $G_p = (V, E_p)$ consisting of a weighted bidirectional graph, where V is the set of network nodes and E_p is set of physical links which connects the nodes. Nodes correspond to network nodes and links corresponds to fiber between the nodes. Links are assigned weights, which may correspond to physical distance between nodes. We have assumed that all links have same weight 1 which corresponds to fiber hop distance. A network node i is assumed to be equipped with optical cross-connects or wavelength-routed switch.
- Number of wavelength channels carried by each fiber is W. Capacity of wavelength is C.
- The number of lasers (transmitters) (TR_i) and filters (receivers) (RR_i) at each node i. The transmitters and receivers used are wavelength-tunable.
- *To Develop:* A virtual topology $G_v = (V, E_v)$. The nodes of virtual topology correspond to nodes in physical topology. A link between node i and j corresponds to a bidirectional lightpath set up between node pair $(i,\ j)$.
- *Objective*: To minimize blocking probability of the given network and to develop RWA algorithm on virtual topology.

Problem Formulation

We have formulated the given problem. The objective of this problem is the minimization and optimization of blocking probability. The following assumptions have been made for problem formulation.

- *Assumptions:*

- The network is single fiber (bidirectional) irregular mesh network, i.e., there is one fiber between each node pair.
- The wavelength-routing switches in network node do not have wavelength conversion capability.
- A connection request cannot be divided into several lower speed connections and routed separately from source to destination.

- *Notations used:*

We have used following notations for mathematical formulation:

- m and n denote endpoints of a physical fiber link that might occur in a lightpath
- i and j denote originating and terminating nodes for a lightpath. A lightpath may traverse single or multiple physical fiber links.
- s and d denotes source and destination of an end-to-end traffic request. The end-to-end traffic may traverse through a single lightpath or multiple lightpath.

- *Given:*

- N: Number of nodes in the WDM network.
- l is the length of route or number of links in the route or path selected.
- r is number of routes available where $r \epsilon R$, where R is total number of routes which can exist.
- W: Number of wavelength per fiber. We assume all the fibers in the network carry same number of wavelengths.
- P_{mn}: Number of fibers interconnecting nodes m and node. $P_{mn} = 0$ for node pair which is not physically adjacent to each other. $P_{mn} = P_{nm} = 1$ if and only if there exist a direct physical link between nodes m and n.
- P_{mn}^{w}: Number of fibers interconnecting node m and node n on a wavelength w. $P_{mn}^{w} = P_{mn}$

- TR_i: Number of transmitters at node i.
- RR_i: Number of receivers at node i. Note that, we have assumed that all nodes are equipped with tunable transceivers, which can be tuned to any of W wavelengths.
- V_{ij}: Number of lightpaths from node i to j in virtual topology.
- V_{ij}^{w}: Number of lightpaths from node i to j on wavelength w. Note that, $V_{ij}^{w} > 1$, lightpath between nodes i to j on wavelength w may take different paths.
- $P_{mn}^{ij,w}$: Number of lightpaths between nodes $(i,\ j)$ routed through fiber link (m, n) on a wavelength w.
- B_{sd}: Blocking probability; $B_{sd} = 0$ if the request from node s to node d has been successfully routed; otherwise, $B_{sd} = 1$, call blocked.
- $B_{sd,w}^{r}$: Blocking probability caused by insufficient wavelength.
- $B_{sd,C}^{r}$: Blocking probability caused due to lack of wavelength converters.
- B_{sd}^{r}: Blocking probability of r routes
- L_{sd}^{r}: Load of the route r.

Objective:

Minimize $\sum_{s,d} B_{sd}$ (6.1)

➢ *Constraints:*

There are some constraints on virtual-topology connection variables and physical route variables which are given by equation (6.2) – equation (6.11).

- *On virtual-topology connection variables:*

The number of lightpaths between node pair $(i,\ j)$ is less than or equal to the number of receivers at node j which are given by equation (6.2) – equation (6.3).

$$\sum_j V_{ij} \leq\ TR_i\ \forall\ i \qquad (6.2)$$

$$\sum_i V_{ij} \leq\ RR_j\ \forall\ j \qquad (6.3)$$

The lightpath between $(i,\ j)$ are composed of lightpaths on different wavelengths between the node pair $(i,\ j)$which are given by equation (6.4). The value of V_{ij}^{w}can be greater than 1.

$$\sum_w V_{ij}^{w} = V_{ij}\ \forall\, i,j \tag{6.4}$$

$$int\, V_{ij}, V_{ij}^{w} \tag{6.5}$$

- *On physical route variables:*

The routing of a lightpath from its origin to its destination is given by equation (6.6) – equation (6.10). For an intermediate node k of the lightpath $(i,\ j)$ on wavelength w, number of incoming lightpath streams is equal to the number of outgoing lightpath streams and is given by equation (6.6). For the origin node i of the lightpath $(i,\ j)$ on wavelength w, number of incoming lightpath streams is 0, which is given by equation (6.7). Equation (6.8) states that, for termination node j of the lightpath $(i,\ j)$ on wavelength w, number of outgoing lightpath stream is 0. For origin node i of the lightpath $(i,\ j)$ on wavelength w, number of outgoing lightpath streams is equal to total number of lightpaths between node pair $(i,\ j)$ on wavelength w, which is given by equation (6.9).

$$\sum_m P_{mk}^{ij,w} = \sum_m P_{kn}^{ij,w} \text{ if } k \neq i,j\ \forall\, i,j,w,k \tag{6.6}$$

$$\sum_m P_{mi}^{ij,w} = 0\ \ \forall\, i,j,w \tag{6.7}$$

$$\sum_n P_{jn}^{ij,w} = 0\ \ \forall\, i,j,w \tag{6.8}$$

$$\sum_n P_{in}^{ij,w} = V_{ij}^{w}\ \ \forall\, i,j,w \tag{6.9}$$

The equation (6.10) ensures that, for termination node j of the lightpath $(i,\ j)$ on wavelength w, number of incoming lightpath streams is equal to the number of lightpaths between node pair $(i,\ j)$ on wavelength w. Also, equation (6.11) ensures that wavelength w on one fiber link (m, n) can only be present in one lightpath in the virtual topology.

$$\sum_m P_{mj}^{ij,w} = V_{ij}^w \quad \forall\, i,j,w \tag{6.10}$$

$$\sum_{i,j} P_{mn}^{ij,w} \leq P_{mn}^w \quad \forall\, m,n,w \tag{6.11}$$

6.4.2. Proposed Approaches

In this section, we have proposed a mathematical model which is used for minimization and optimization of blocking probability followed by simple GRWA algorithms. The proposed approaches are then illustrated by applying them on a suitable 6-node network.

6.4.2.1 Proposed Mathematical Model

We have proposed a mathematical model for wavelength–routed all–optical WDM network without wavelength conversion. For a given WDM optical network, a physical topology $G_p = (V, E_p)$ consisting of a weighted bidirectional graph, where V is a set of network nodes and E_p is set of physical links which connects these nodes. Links are assigned weights which correspond to physical distance between nodes. We have assumed that all links have same weight 1 which corresponds to fiber hop distance. A network node i is assumed to be equipped with optical cross-connects or wavelength-routed switch. Number of wavelength channels carried by each fiber is W. We have adopted fixed-alternate path routing policy for lightpath establishment; predetermined directed routes are indicated with a set R. For each route $r \in R$, blocking probability for connections along route r can be divided into two mutual exclusive parts; $B_{sd,w}^r$ and $B_{sd,C}^r$. The total blocking probability for a network with wavelength conversion is given by:

$$B_{sd}^r = B_{sd,w}^r + B_{sd,C}^r \tag{6.12}$$

$$B_{sd} = \left(\frac{\sum_{r \in R} L_{sd}^r B_{sd}^r}{\sum_{r \in R} L_{sd}^r} \right) \tag{6.13}$$

$$B_{sd} = \left\{ \frac{\sum_{r \in R} L_{sd}^r \left(B_{sd,w}^r + B_{sd,C}^r \right)}{\sum_{r \in R} L_{sd}^r} \right\} \tag{6.14}$$

As we are not using wavelength conversion so the equation (6.14) is reduced to equation (6.15)

$$B_{sd} = \left\{\frac{\sum_{r\in R} L_{sd}^{r}\left(B_{sd,w}^{r}\right)}{\sum_{r\in R} L_{sd}^{r}}\right\} \tag{6.15}$$

Also, blocking probability can be calculated by Erlangs–B formula as equation (6.16).

$$B_{sd,w}^{r} = \frac{\frac{\left(L_{sd}^{r}\right)^{W}}{W!}}{\sum_{i=0}^{W}\frac{\left(L_{sd}^{r}\right)^{i}}{i!}} \tag{6.16}$$

Using equation (6.15) and equation (6.16) B_{sd} can be reduced to

$$B_{sd} = \left[\frac{\sum_{r\in R} L_{sd}^{r}\left\{\frac{\frac{\left(L_{sd}^{r}\right)^{W}}{W!}}{\sum_{i=0}^{W}\frac{\left(L_{sd}^{r}\right)^{i}}{i!}}\right\}}{\sum_{r\in R} L_{sd}^{r}}\right] \tag{6.17}$$

Equation (6.17) gives mathematical model which can be used for minimization and optimization of blocking probability.

6.4.2.2 Proposed GRWA-I

The RWA problem has been studied and investigated by several researchers. Most of studies decomposed the RWA problem into two sub-problems; namely routing problem and wavelength assignment problems. We have proposed a GRWA-I algorithm which deals with problem of traffic grooming, routing and wavelength assignment problem as a single problem without decomposing it into different problems. Our algorithm can be described as follows:

Algorithm: GRWA-I

Definitions:

$U_{s,d}$: Unprocessed pair; $U_{s,d}$= 1 for unprocessed s-d pair; $U_{s,d}$= 0 for processed s-d pair

U_p: Unprocessed path; U_p= 1 for unprocessed path; U_p=0 for processed path.

Step 1: Pre Processing

```
1.1   Start
1.2   Generate all source-destination pairs (s, d);
1.3   Find all paths ($P_{s,d}$) for every pair;
1.4   Calculate Number of hops for every path;
1.5   Save Number of hops in a matrix ($N_H$);
```

Step 2: Routing and Wavelength Assignment

```
2.1   Set $U_{s,d}$=1for every s-d pair;
2.2   Set $U_p$=1 for every path of every s-d pair;
2.3   Sort matrix $N_H$ in increasing order;
2.4   Assign different values of load $L_{sd}^r$ to unprocessed path ($s_1$, $d_1$);
2.5   Fix the number of wavelengths ($W$);
2.6   Sort wavelengths in increasing order;        // (as $W_1, W_2$…)
2.7   For (every s-d pair having $U_{sn,dn}$=1)      // ($s_n$,$d_n$ represents the $n^{th}$
                                                       pair)
          {
2.8       For (every path having $U_{pq}$=1)          // $P_q$ represents the $q^{th}$ path
              {
2.9           Calculate the blocking probability $B_{sd}$ of the system using
                  the given formula;
2.10              Save blocking probability $B_{sd}$ in a matrix $B_T$ with the s-d
                  pair and path;
2.11              Set $U_{pq}$=0;
              }
2.12      Set $U_{sn,dn}$=0;
              }
2.13  Select required s-d pair;
2.14  Select minimum value of blocking probability $B_{sd}$ from a matrix $B_T$;
2.15  Select corresponding path for the minimum value of $B_{sd}$;
2.16  If (call blocked)
          {
          Select the next path with next blocking probability from matrix $B_T$;
          }
2.17  Else
          {
2.18      Select the path and assign lowest available wavelength ($W_n$) to the
          selected route path;
2.19      }
2.20  End
```

A. Time Complexity of the Algorithm

Time complexity of the algorithm has been calculated and depicted by Big-O notation.

We can compute the time complexity as for step 1.2 and step 1.3 the time complexity is given by $O(N)$, $O(R)$, respectively. The time complexity of step 2.3 is given by $O(2\log N)$ for the step 2.6 is $O(\log W)$ and for step 2.7 to 2.20 its worse value is $O(R)$. The number of possible routes can be calculated as $R = \frac{N(N-1)}{2}$, therefore in worse case the time complexity of algorithm is given by $O(N^2) + O(\log W)$.

6.4.2.3 Proposed GRWA-II

Algorithm: GRWA-II

Definitions:

$U_{s,d}$: Unprocessed pair; $U_{s,d}$= 1 for unprocessed s-d pair; $U_{s,d}$= 0 for processed s-d pair

U_p: Unprocessed path; U_p= 1 for the unprocessed path; U_p=0 for the processed path.

Step 1: Pre Processing

```
1.6    Start
1.7    Generate all source-destination pairs (s, d);
1.8    Find all paths ($P_{s,d}$) for every pair;
1.9    Calculate Number of hops for every path;
1.10   Save Number of hops in a matrix ($N_H$);
```

Step 2: Routing and Wavelength Assignment

```
2.21   Set $U_{s,d}$=1for every s-d pair;
2.22   Set $U_p$=1 for every path of every s-d pair;
2.23   Sort matrix $N_H$ in increasing order;
2.24   Assign fixed value of load $L_{sd}^r$ to unprocessed path ($s_1$, $d_1$);
2.25   Fix number of channels ($C$);
2.26   Sort channels in increasing order;          // (as $C_1$, $C_2$...)
2.27   For (every s-d pair having $U_{sn,dn}$=1)    // ($s_n$,$d_n$ represents the n^th pair)
       {
2.28       For (every path having $U_{pq}$=1)      // $P_q$ represents the q^th path
           {
2.29           Calculate the blocking probability $B_{sd}$ of the system for
               every path using the given formula, i.e.
               $B_{sd} = 1 - \left[1 - \frac{\frac{\left(\frac{N\lambda}{l}\right)^C}{C!}}{\sum_{i=0}^{C}\frac{\left(\frac{N\lambda}{l}\right)^i}{i!}}\right]^l$ ;
2.30           Save blocking probability $B_{sd}$ in a matrix $B_T$ with the s-d
```

```
                        pair and different path;
2.31                    Set $U_{pq}$=0;
                    }
2.32            Set $U_{sn,dn}$=0;
        }
2.33    Repeat step 2.4 to 2.12 for variable Load $L_{sd}^{r}$ to unprocessed path ($s_1$, $d_1$) and
        save the blocking probability $B_{sd}$ in a matrix $B_{T1}$ with the s-d pair and different
        path;
2.34    Select the required s-d pair;
2.35    Compare the value of blocking probability $B_{sd}$ from a matrix $B_T$ and $B_{T1}$ and
        select the minimum value of $B_{sd}$.
2.36    Select corresponding path for the minimum value of $B_{sd}$;
2.37    If (call blocked)
            {
            Select the next path with next blocking probability from matrix $B_T$;
            }
2.38    Else
            {
2.39        Select the path and assign channels with lowest blocking probability ($C_n$)
            to the selected route path;
2.40        }
2.41    End
```

6.4.3. Simulation Results of GRWA-I and GRWA-II

In this section, simulation results for proposed GRWA-I and GRWA-II algorithms have been discussed. We have considered a network without wavelength conversion. The total blocking probability of network depends on $B_{sd,w}^{r}$, i.e. blocking probability caused by insufficient wavelength. We have applied proposed approaches on given 6-node network shown in figure (6.19).

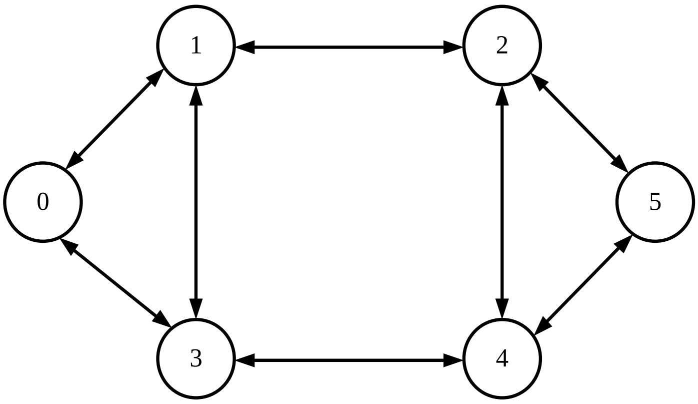


Figure 6.19: A 6-node network.

Table 6.8: Virtual paths, Actual paths and number of hops for GRWA

s-d pairs	**Virtual paths**	**Actual paths**	**Number of hops**	**s-d pairs**	**Virtual paths**	**Actual paths**	**Number of hops**
0-1	0-1	0-1	1	1-4	1-2-4	1-2-4	2
	0-3-1	0-3-1	2		1-3-4	1-3-4	2
	0-3-4-2-1	0-3-4-2-1	4		1-0-3-4	1-0-3-4	3
	0-3-4-5-2-1	0-3-4-5-2-1	5		1-2-5-4	1-2-5-4	3
0-2	0-1-2	0-1-2	2	1-5	1-2-5	1-2-5	2
	0-3-4-2	0-3-4-2	3		1-3-4-5	1-3-4-5	3
	0-3-1-2	0-3-1-2	3		1-2-4-5	1-2-4-5	3
	0-1-3-4-2	0-1-3-4-2	4		1-3-4-2-5	1-3-4-2-5	4
	0-3-4-5-2	0-3-4-5-2	4		1-0-3-4-5	1-0-3-4-5	4
	0-1-3-4-5-2	0-1-3-4-5-2	5		1-0-3-4-2-5	1-0-3-4-2-5	5
0-3	0-3	0-3	1	2-3	2-1-3	2-1-3	2
	0-1-3	0-1-3	2		2-4-3	2-4-3	2
	0-1-2-4-3	0-1-2-4-3	4		2-1-0-3	2-1-0-3	3
	0-1-2-5-4-3	0-1-2-5-4-3	5		2-5-4-3	2-5-4-3	3
0-4	0-3-4	0-3-4	2	2-4	2-4	2-4	1
	0-1-2-4	0-1-2-4	3		2-5-4	2-5-4	2
	0-1-3-4	0-1-3-4	3		2-1-3-4	2-1-3-4	3
	0-3-1-2-4	0-3-1-2-4	4		2-1-0-3-4	2-1-0-3-4	4
	0-1-2-5-4	0-1-2-5-4	4	2-5	2-5	2-5	1
	0-3-1-2-5-4	0-3-1-2-5-4	5		2-4-5	2-4-5	2
0-5	0-1-2-5	0-1-2-5	3		2-1-3-4-5	2-1-3-4-5	4
	0-3-4-5	0-3-4-5	3		2-1-0-3-4-5	2-1-0-3-4-5	5
	0-1-2-4-5	0-1-2-4-5	4	3-4	3-4	3-4	1
	0-3-4-2-5	0-3-4-2-5	4		3-1-2-4	3-1-2-4	3
	0-1-3-4-5	0-1-3-4-5	4		3-1-2-5-4	3-1-2-5-4	4
	0-3-1-2-5	0-3-1-2-5	4		3-0-1-2-4	3-0-1-2-4	4
	0-1-3-4-2-5	0-1-3-4-2-5	5		3-0-1-2-5-4	3-0-1-2-5-4	5
	0-3-1-2-4-5	0-3-1-2-4-5	5	3-5	3-4-5	3-4-5	2
1-2	1-2	1-2	1		3-4-2-5	3-4-2-5	3
	1-3-4-2	1-3-4-2	3		3-1-2-5	3-1-2-5	3
	1-0-3-4-2	1-0-3-4-2	4		3-1-2-5-4	3-1-2-5-4	4
	1-3-4-5-2	1-3-4-5-2	4		3-0-1-2-4	3-0-1-2-4	4
	1-0-3-4-5-2	1-0-3-4-5-2	5		3-0-1-2-5-4	3-0-1-2-5-4	5
1-3	1-3	1-3	1	4-5	4-5	4-5	1
	1-0-3	1-0-3	2		4-2-5	4-2-5	2
	1-2-4-3	1-2-4-3	3		4-3-1-2-5	4-3-1-2-5	4
	1-2-5-4-3	1-2-5-4-3	4		4-3-0-1-2-5	4-3-0-1-2-5	5

The table (6.8) shows virtual path, actual path and the number of hops for all possible source-destination pairs for both GRWA-I and GRWA-II. The figure (6.20) and figure (6.21) shows blocking probability distribution of source-destination pairs for all possible paths for varying wavelengths and fixed load. We can note that blocking probability of given s-d pair from figure (6.20) and figure (6.21) and hence we can check for the minimum blocking probability for s-d pair. In this way we can judge the best possible path for s-d pair with minimum blocking probability. Figure (6.20) shows blocking probability variation for different paths with source node as 1 and destination node as 2, 3, 4 or 5. Figure (6.21) shows blocking probability for different paths with source as 2, 3 and 4 and destination may be 3, 4 or 5. Figure (6.22) shows blocking probability distribution of all possible paths for fixed wavelengths and varying load.

6.4.3.1 Results and Discussion for GRWA-I

Table (6.9) compares blocking probability of different s-d pairs for variable and fixed load. Node 0 is taken as source for this comparison. This comparison is also illustrated in figure (6.23) and figure (6.24). The blocking probability of system is comparatively less in case of variable load for all routing paths but its value is least for a route (0-1-3-4-5-2) in both the cases. The blocking probability of system is same and its value is 0.306748(%). The comparison has been made between RWA & GRWA-I in figure (6.25). The comparison shown in figure (6.25) depicts that blocking probability of a network increases with route length in case of RWA, whereas its value goes on decreasing with increase in route length in our proposed GRWA-I algorithm. The value of blocking probability in GRWA-I is very small as compared to blocking probability in RWA for every route length. Also, figure depicts that the algorithm is very effective for networks with higher route length because the value of blocking probability decreases with increase in route length. The blocking probability distribution of all source-destination pairs for fixed and varying load is given in figure (6.26) and figure (6.27) respectively. The proposed approaches can easily be illustrated by taking a particular s-d path as 0-2, 0-5, 3-4 and 3-5. These examples are illustrated by table (6.9) and figure (6.28)-(6.29). Figure (6.28) compares blocking probability distribution of all possible paths for source destination pairs as 0-2 for fixed and varying load whereas, figure

(6.29) compares blocking probability of all possible paths for s-d pairs as 0-5 for fixed and variable load.

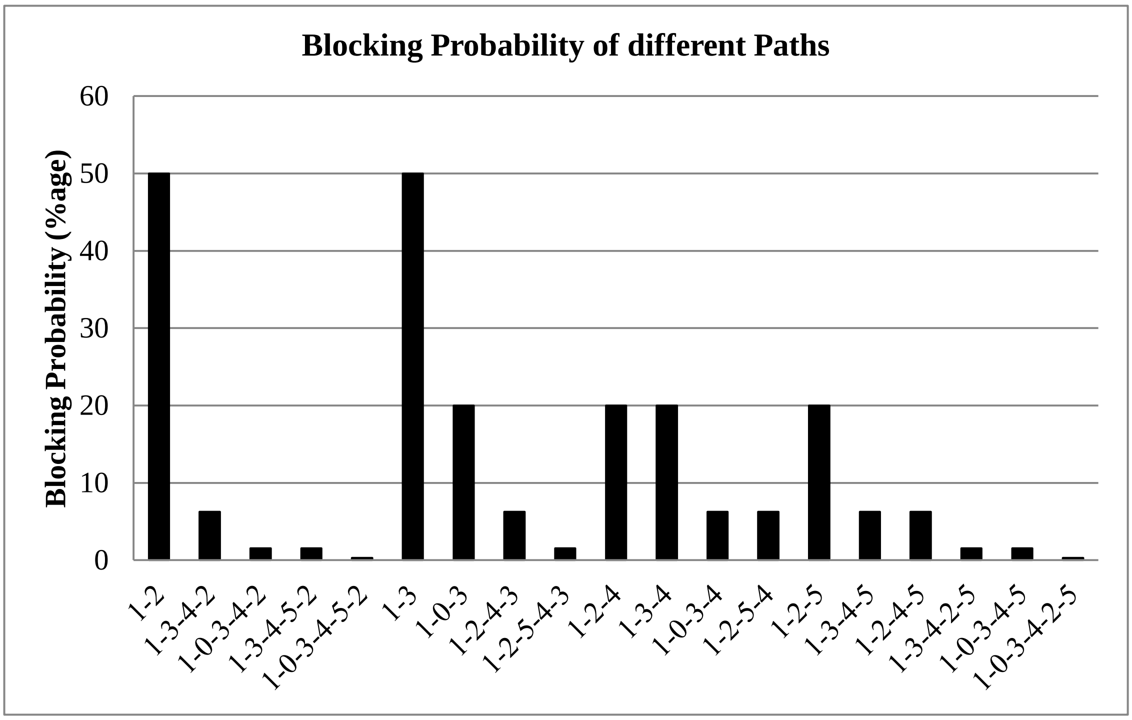


Figure 6.20: Blocking probability of different paths for varying wavelengths and fixed load for GRWA-I

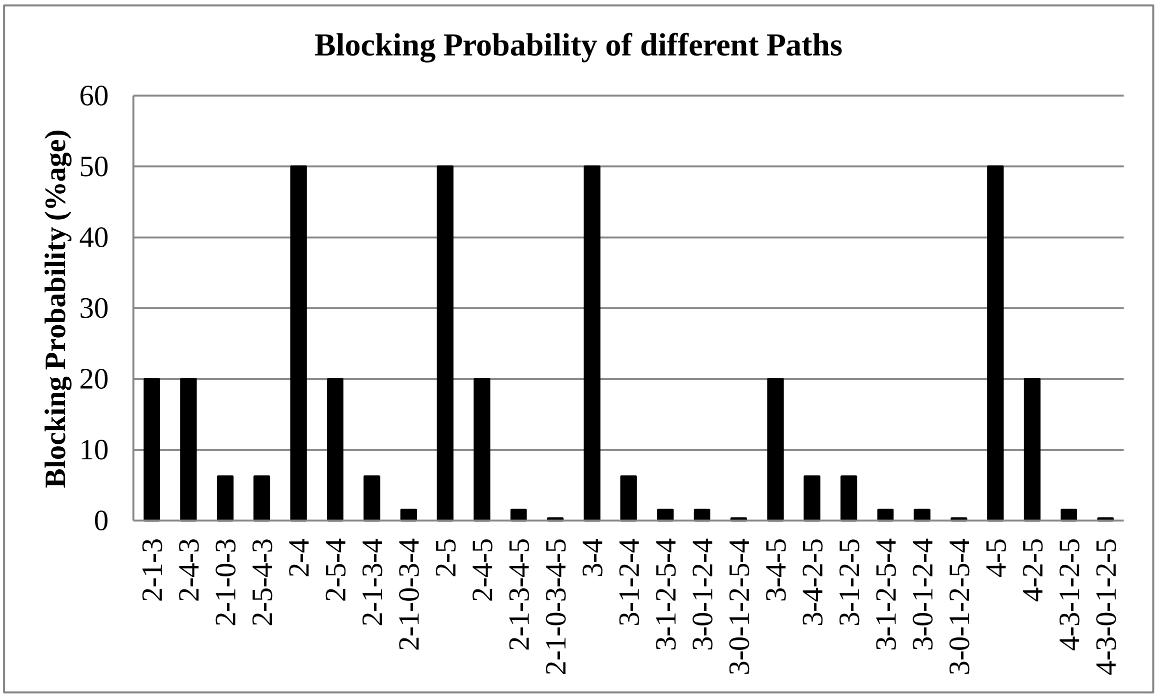


Figure 6.21: Blocking probability of different paths for varying wavelengths and fixed load for different s-d pairs for GRWA-I

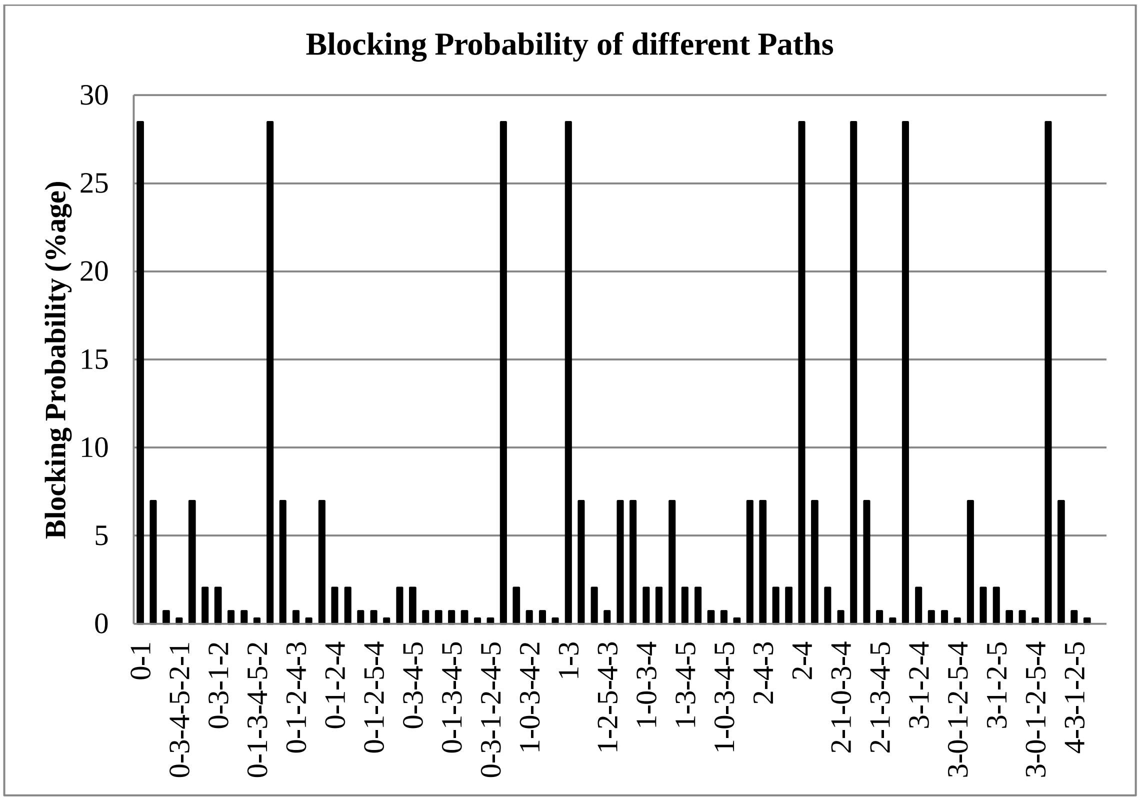


Figure 6.22: Blocking probability of different paths for fixed wavelengths and varying load for GRWA-I

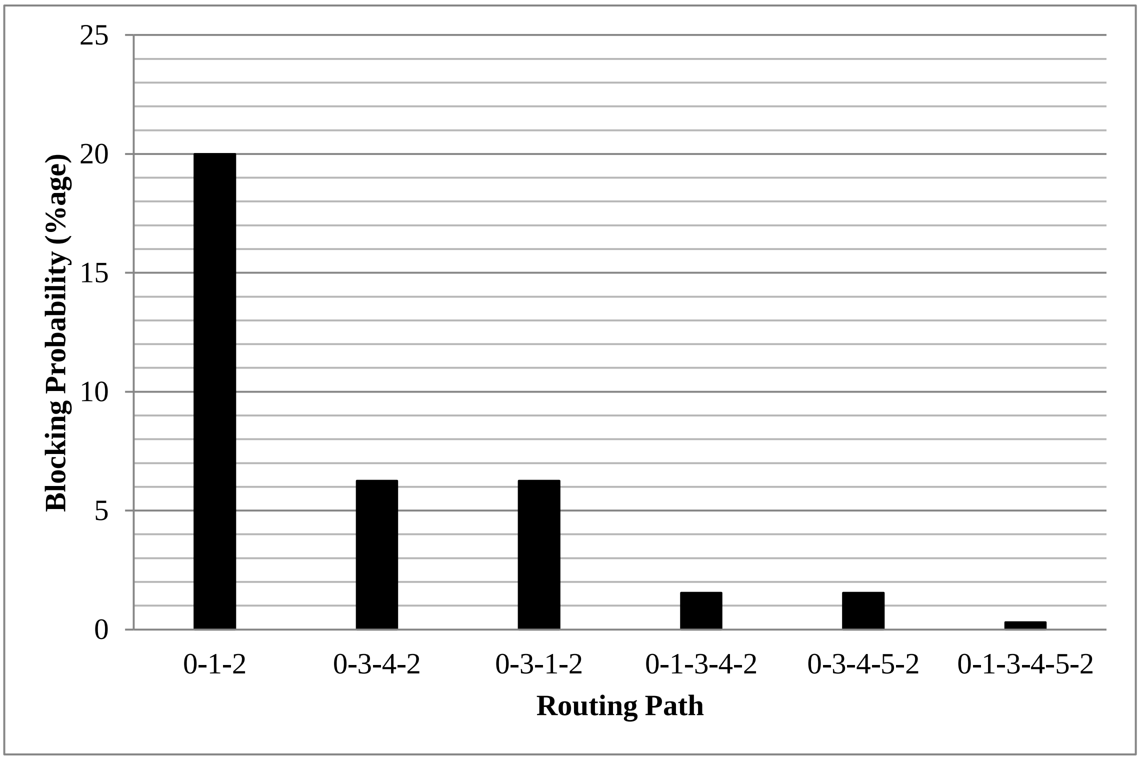


Figure 6.23: Blocking probability of different paths for varying wavelengths and fixed load.

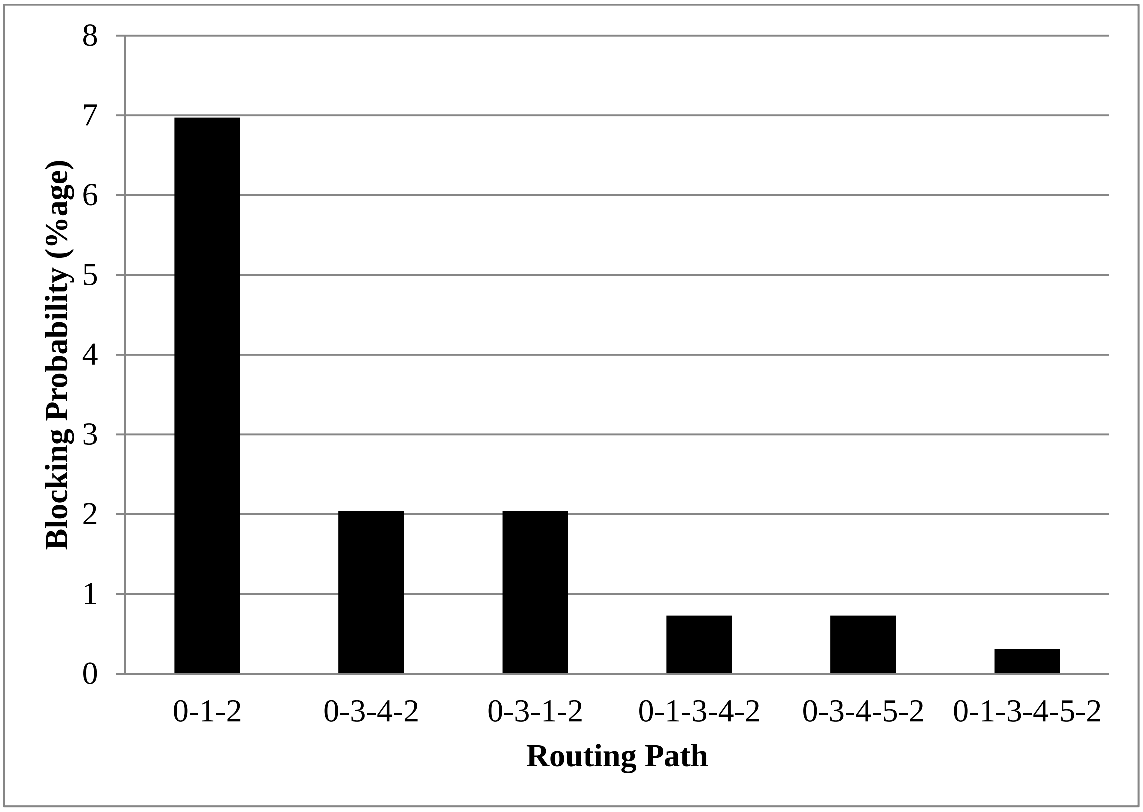


Figure 6.24: Blocking probability of different paths for varying load and fixed wavelength.

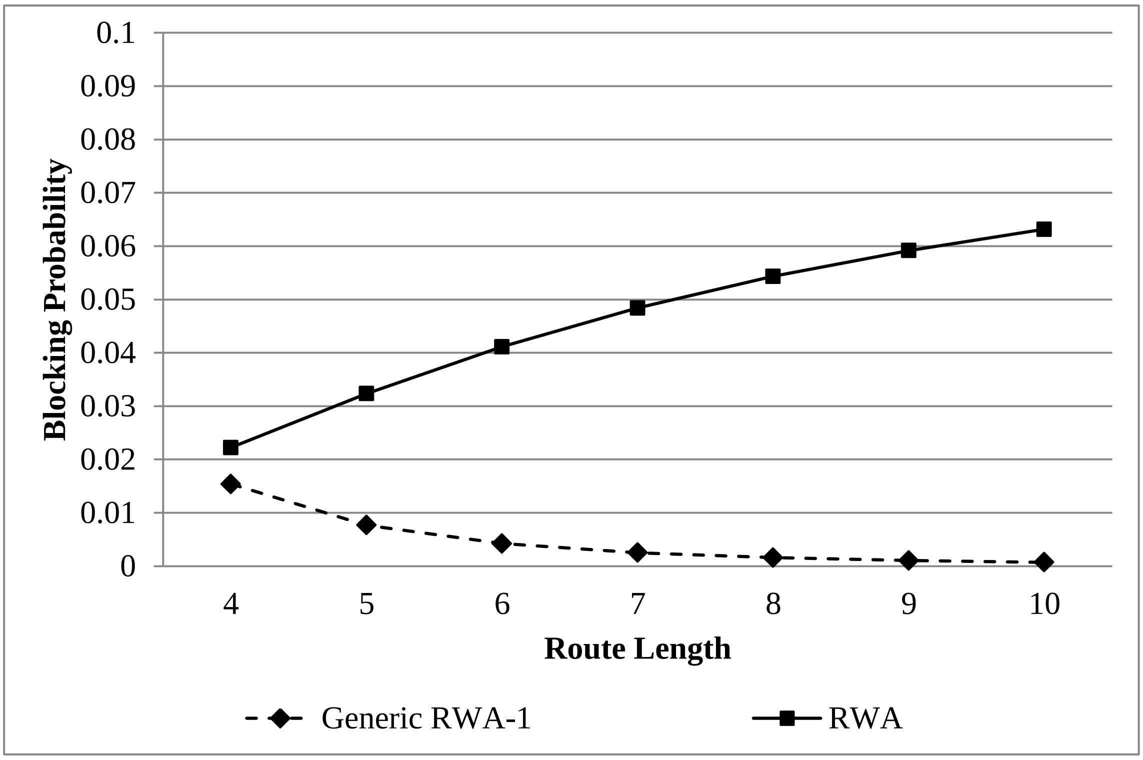


Figure 6.25: Comparison of blocking probability of RWA and GRWA-I

Table 6.9: Comparison of blocking probability of different s-d pairs for variable and fixed load for GRWA-I

s-d pairs	**Virtual paths**	**Practical paths**	**Number of hops**	***W***	**Load**	**Blocking Probability for variable load and fixed *W*. (%age)**	***W***	**Load**	**Blocking Probability for fixed load and variable *W*. (%age)**
0-2	0-1-2	0-1-2	2	5	2.5	6.973112	2	1	20
0-2	0-3-4-2	0-3-4-2	3	5	1.67	2.039019	3	1	6.25
0-2	0-3-1-2	0-3-1-2	3	5	1.67	2.039019	3	1	6.25
0-2	0-1-3-4-2	0-1-3-4-2	4	5	1.25	0.729961	4	1	1.538462
0-2	0-3-4-5-2	0-3-4-5-2	4	5	1.25	0.729961	4	1	1.538462
0-2	0-1-3-4-5-2	0-1-3-4-5-2	5	5	1	**0.306748**	5	1	**0.306748**

Table 6.10: Comparison of blocking probability with fixed and variable load for GRWA-II

S-d pairs	**Paths**	**Blocking probability with fixed load (% age)**	**Blocking probability with variable load (% age)**
3-4	3-4	1.838457034	1.838457034
3-4	3-1-2-4	5.414594758	0.00258237
3-4	3-1-2-5-4	0.016897677	0.000294123
3-4	3-0-1-2-4	0.016897677	0.000294123
3-4	3-0-1-2-5-4	0.02112165	5.06888E-05
3-5	3-4-5	3.643114825	0.043143042
3-5	3-4-2-5	5.414594758	0.00258237
3-5	3-1-2-5	5.414594758	0.00258237

6.4.3.2 Results for GRWA-II

Table (6.10) shows a comparison of blocking probability of different paths for variable and fixed load for 3-4 and 3-5 as s-d pairs. It is clear from the results shown in figure (6.26)-(6.29) and table (6.10) that blocking probability of the system is comparably less

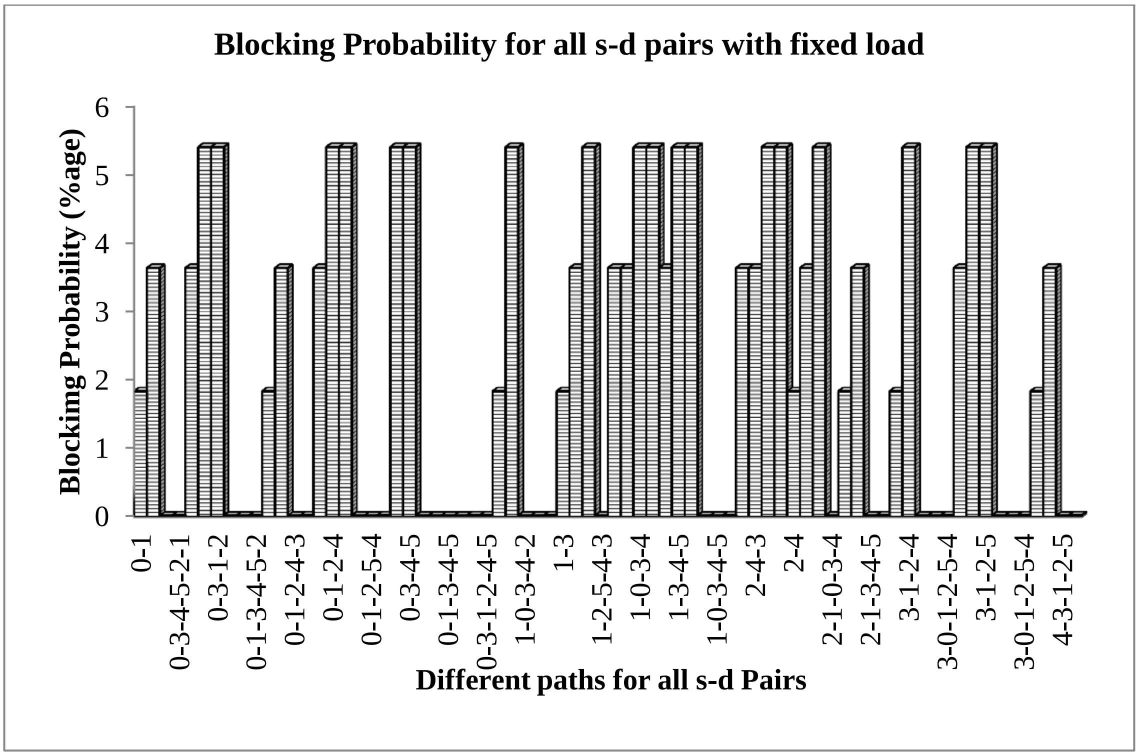


Figure 6.26: Blocking probability of all s-d pairs for fixed load for GRWA-II

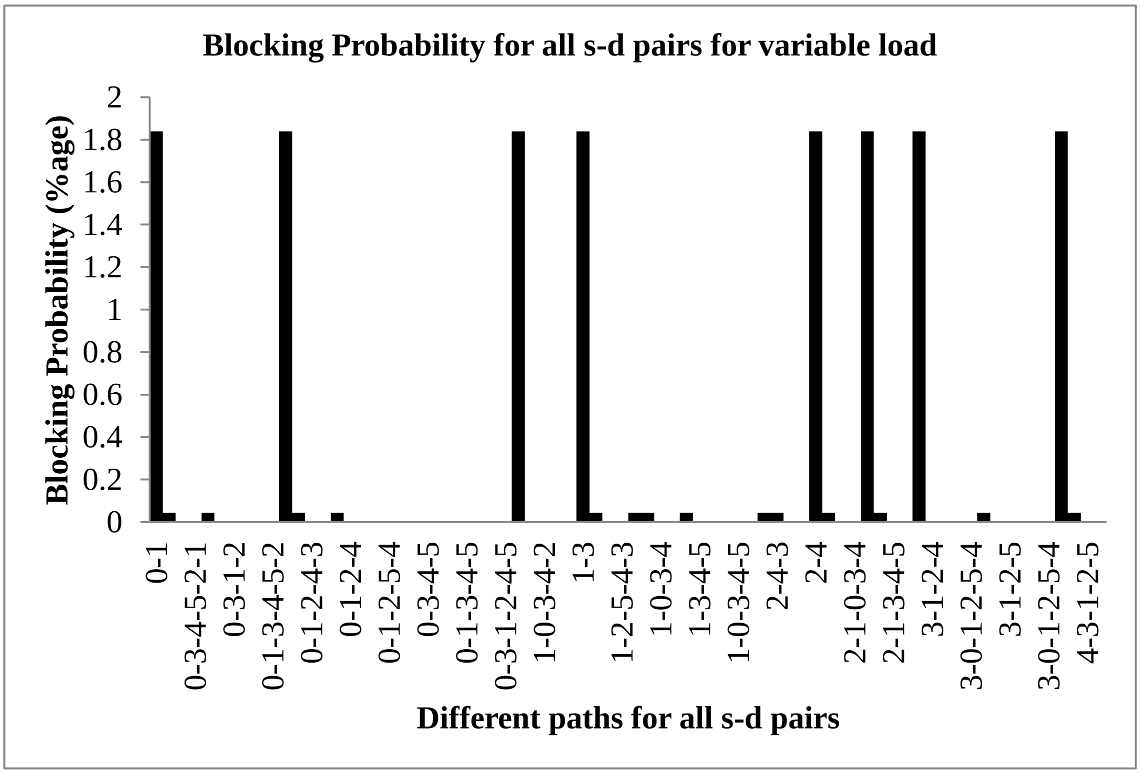


Figure 6.27: Blocking probability of all s-d pairs for varying load for GRWA-II

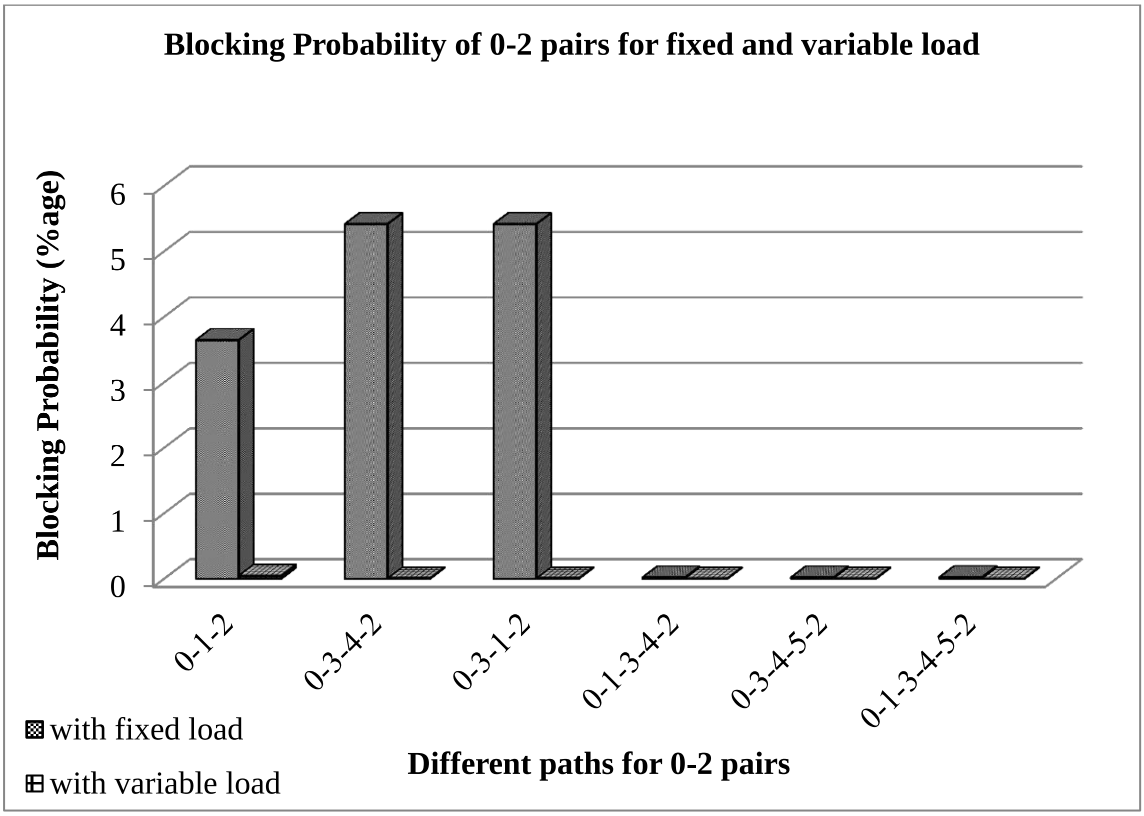


Figure 6.28: Blocking probability of 0-2 pairs for fixed and variable load for GRWA-II

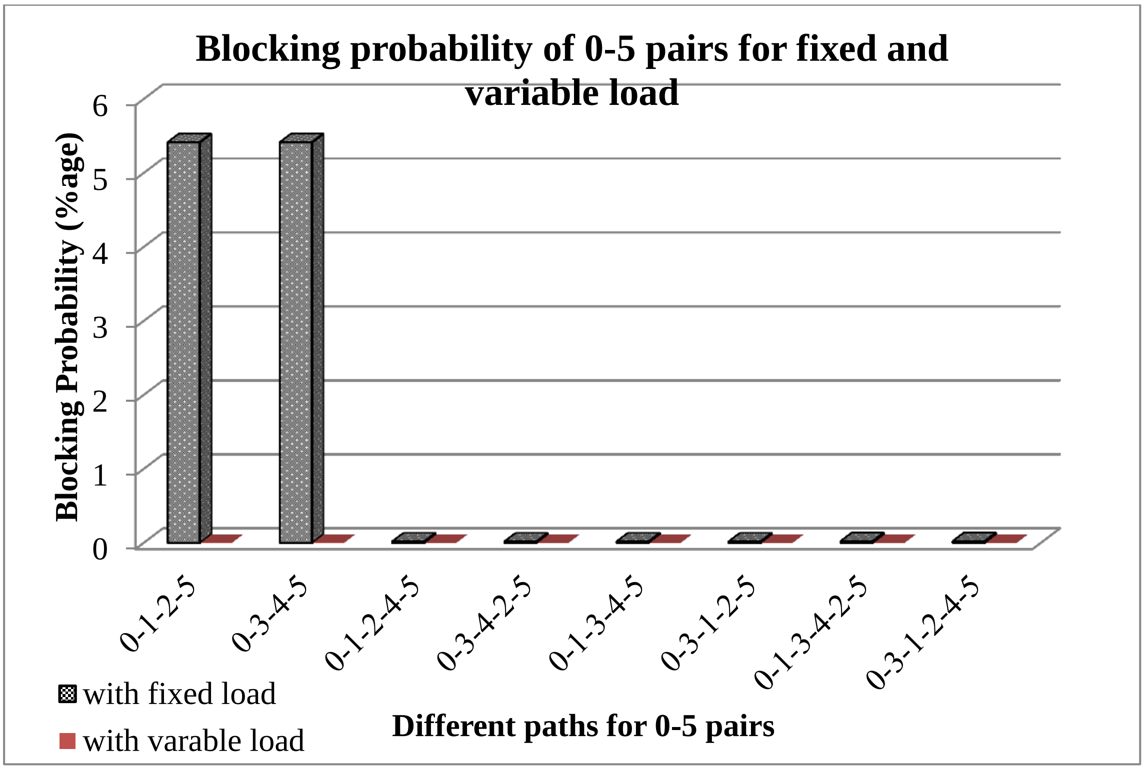


Figure 6.29: Blocking probability of different paths for 0-5 pair for fixed and variable load for GRWA-II

in case of variable load for all routing paths and s-d pairs. As shown in the table (6.10) for the s-d pair 3-5 the minimum blocking probability of the system for fixed load is 3.64% for path 3-4-5 whereas, its value is 0.0026% for path 3-4-2-5 and 3-1-2-5.

6.5. Conclusions

In this chapter, we have investigated the third objective in order to develop new solutions for RWA problem treating it as a single problem. Different solutions for RWA problem have been proposed. Some of the models which have been used for calculation and optimization of blocking probability are from chapter III of this thesis. This chapter is divided into three sections. In the first section an algorithm named IFARWA has been proposed which is an improvement of fixed-alternated RWA. This algorithm has then been implemented on realistic networks such as: NSFNET and EUPAN. In the second section the problem of enhancing multiple-fault restorability in path protected wavelength–routed all optical WDM networks has been discussed. Two solutions for this multiple link failure problem named fault-tolerant RWA and survivable RWA have been proposed. The only assumption made for NSFnet is that one of the first three links must be fault-free. Using this RWA algorithm the blocking probability of the network has been reduced to a large extent. We have also analysed the response of blocking probability of NSFnet for variable load. As the load per link (in Erlangs) increases blocking probability increases in the earlier algorithms; whereas, blocking probability decreases with the proposed FTRWA algorithm. The proposed algorithm is then compared with the existing routing and wavelength assignment algorithm and results proved that the response of proposed algorithm is better than first-fit and best-fit algorithm. In the third section traffic grooming, routing and wavelength assignment problem has been taken as a single problem and two solutions are proposed: GRWA-I and GRWA-II. These approaches have been implemented on a 6-node network which leads to the reduction of blocking probability. We have also analysed that the blocking probability is comparatively less in case of variable load for all routing paths but the minimum value same for both the cases. The time complexity of the algorithm was calculated and is given by $O(N^2) + O(\log W)$. Also, these models were effective for larger networks as the value of blocking probability in case the proposed model decreases with the increase in route length.

CHAPTER VII

CONCLUSIONS, RECOMMENDATIONS AND FUTURE SCOPE

In this chapter the conclusions, recommendations and future scope of the research are listed.

7.1. Conclusions

All optical wavelength routed network play an important role in the future data communication networks. They offer huge capacity with high scalability which makes them a very attractive choice for the next generation optical networks. The wavelength division multiplexing technique is considered to be one of the best possible techniques in optical network to enhance the capacity of optical fiber. Traffic grooming, routing and wavelength assignment problems are the major problems of WDM networks. In this thesis the wavelength routed networks have been studied and different solutions have been suggested for RWA problem. The solutions to the problem of routing and wavelength assignment have been proposed by dealing it as a single problem as well as by dividing this problem into two different problems; routing problem and wavelength assignment problem. Nonetheless, the promising future of WDM networks makes them an interesting topic for the research.

In this thesis, various performance related issues have been considered which arise in wavelength division multiplexed networks. The problem of routing and wavelength assignment has been discussed as two different problems as well as a complete single problem. All these solutions have been implemented on optical WDM networks to improve their blocking performance. The obtained results have indicated that proposed probabilistic models, routing schemes, wavelength assignment strategies and RWA algorithms can reduce the blocking probability of the network to a very large extent and can make the traffic very smooth. Hence the performance of the optical WDM networks can be improved in terms of blocking.

The following conclusions are based on the results achieved in the individual chapters of the thesis.

1) Considering the problem related to the mathematical models for minimization and optimization of blocking probability of the network, low complexity probabilistic mathematical models have been proposed. These models have been proposed for the calculation and reduction of blocking probability of WDM optical network. These models have been proposed for both wavelength convertible networks as well as for wavelength non-convertible networks. Four mathematical models have been proposed, two of the models for wavelength non–convertible WDM Networks, one model for wavelength convertible WDM networks and one of the models has been proposed which can be implemented on both wavelength convertible and wavelength non–convertible WDM Networks. These mathematical models proposed have closed-form expression and they do not require any simulated statistics. They have low implementation complexity and the computations used are quite efficient. These models suggest the best path for routing and the appropriate number of free wavelengths required for the network. These models can be used to evaluate blocking performance of any network topology. These models have been implemented on practical network topology such as NSFnet and EUPAN. Also these models have proved to be the models for the improvement in performance of the given network topology. The results showed that the models work well for the larger networks having higher number of wavelengths and even for large load per link. So, these models can efficiently be implemented on a network where larger load per link is applied. The value of blocking probability can be reduced to a very small value comparable to zero using these models. Also it has been shown that the computation efficiency of these proposed models is very high as compared to the other models.

2) Two effective algorithms named MUWC and FFWC have been proposed and the performance of these new wavelength assignment algorithms has been evaluated in terms of blocking probability and fairness. The results of proposed algorithm have been compared with conventional wavelength assignment algorithms such as first-fit, best-fit, random and most-used wavelength assignment algorithms. These proposed approaches found very effective for minimization of blocking probability

of optical WDM networks. The blocking response of a network having 10 nodes and for variable load for existing wavelength assignment algorithms has been analysed. Two new wavelength assignment strategies which used sparse wavelength conversion have been proposed which proved to be very effective as compared to the earlier algorithms. The proposed algorithms have also been compared with the conventional algorithms and the results proved that the proposed algorithms work well as compared to them.

3) Further, two wavelength routing algorithms have been proposed for survivable networks in case of dynamic provisioning of lightpath. These algorithms proved to be very efficient in calculation and minimization of blocking probability and produced effective results. To improve the performance of all optical survivable WDM networks techniques based on wavelength rerouting have been proposed. Wavelength rerouting approach as compared to the solution based on wavelength conversion at network nodes found to be a viable and cost effective way to reduce the wavelength continuity constraint considerably. Also this technique consequently improved the blocking performance of the network. Two rerouting algorithms named shortest path wavelength rerouting algorithm and lightpath rerouting algorithm have been proposed for dynamic provisioning of lightpath in WDM optical networks. These wavelength rerouting algorithms can be employed on realistic networks easily and it has been proved by implementing these algorithms on WDM optical network. These algorithms have been used to investigate blocking performance and resource utilization. The key advantage of these algorithms as compared to routing and wavelength assignment algorithm is that these are very simple in nature and require less service disruption time. The results have also proved that proposed rerouting algorithms can also be implemented to huge networks for better blocking performance of the network.

4) Grooming and RWA strategy have been tackled as a single problem. The different RWA strategies have been proposed to evaluate the blocking performance of realistic networks topology such as NSFnet and EUPAN. These strategies have been implemented on these networks to improve their performance on the basis of blocking probability. Further a problem of enhancing multiple-fault tolerance in path

protected wavelength–routed all optical WDM networks has been discussed. Also different mechanisms have been proposed which were used to combat multiple link failures such as fault tolerant RWA algorithm and survivable RWA algorithm. The comparison of these algorithms has also been made with conventional algorithms. These algorithms have been implemented on optical networks with multiple faults and found effective when variable load was applied to different nodes. These algorithms worked well for network where load applied to the nodes changes abruptly. Two Generic RWA (GRWA-I and GRWA-II) have been proposed for optimization and minimization of blocking probability. Using these RWA strategies the blocking probability can be reduced to a large extent. The proposed algorithms have also been compared with conventional routing and wavelength assignment algorithm.

7.2. Recommendations

The following are some of the possible recommendations based on the individual chapters in thesis.

1) The proposed mathematical models are low complexity probabilistic mathematical models. The models reported in this thesis prove to be the best mathematical models due to their simplicity and good performance. These models can be implemented on any network to improve the blocking performance of that network. The strong points of these models are their low complex nature, their efficiency in terms of blocking probability and their flexibility to be used to any network.

2) The proposed MUWC and FFWC wavelength assignment strategies are the best possible strategies because these strategies do not use full wavelength conversion which reduces the cost of the network. These strategies can reduce the blocking probability of the network nearly by 30%. The time complexity of the proposed strategies is very less. These strategies are very easy to implement on any network topologies.

3) The SPWRR and LRRA schemes proposed in this thesis are recommended for the improvement of performance of the faulty networks. These schemes are the best

possible schemes in those networks where multiple faults occur. These rerouting schemes are the best possible schemes for dynamic traffic in WDM optical network as they make the network to be survivable and hence improve the blocking performance of that network. The time complexity of these proposed schemes is very small so these schemes can be applied to the huge networks with heavy load. Also we can use these schemes for the faulty network to increase their blocking performance.

4) The RWA algorithms proposed in this thesis are recommended as more suitable for various network applications with large network load and for better security of data. We have proposed FTRWA and SRWA algorithms which can be used for the networks where there is possibility of recurrence of fault. These proposed solutions to RWA problem are very effective for larger and faulty networks. Further we have proposed GRWA-I and GRWA-II for the optimization and minimization of blocking probability. These algorithms are recommended for the system where the load changes abruptly. Thus the proposed schemes provide flexible solution suitable for handling the varying traffic demands of the next-generation optical network.

7.3. Future Scope

The following are some of the possible areas of future work based on the individual chapters in the thesis.

The probabilistic mathematical models have been suggested and proposed for better performance of the network in term of blocking probability. In WDM network, an additional performance measure is the capacity which can be increased to a particular extent for the future networks. Future work may include the designing of mathematical models for increasing the capacity of optical WDM network. These mathematical models can also be used for IP-over-WDM networks. Also the proposed models can be implemented on OBS networks and passive optical networks. The proposed models can also be extended for the capacity allocation in mesh-based survivable networks.

Possible areas of future work are the analysis of the wavelength reuse schemes. These wavelength reuse schemes in combination with wavelength conversion schemes can produce better results. The proposed models can be extended to wavelength reuse schemes for optical bust switching networks and optical packet switching networks. Also proposed wavelength assignment schemes can be modified to increase the capacity of the optical networks. Wavelength assignment schemes proposed in this chapter can also be extended for restoration and fault tolerance in optical WDM networks.

The rerouting algorithms are proposed which proved to be better than conventional algorithms. These schemes can be extended for resilient communication networks. This work can be extended for investigations of further supporting multiple link failure in an all-optical burst-switched network and passive optical-WDM Networks. These proposed schemes can also be used in increasing the capacity of these networks, not at lowering the cost and performance of the network. The quality of service offered by various priority policies and efficient retransmission scheme can also be improved for WDM networks in order to establish a proper connection between source and destination. The work can also be extended to survivable mesh-based transport Networks.

One of the possible areas of future work is an extension of this work to wavelength colouring problem in WDM network. Also this work can be extended for traffic grooming and colouring. We can also extend these proposed solutions to cycle based protection for optical WDM networks. More schemes can be proposed for fault detection and recovery in WDM optical networks for better performance. The fault tolerant schemes proposed in this thesis can be enhanced for restoration and fault recovery for protected traffic services in GMPLS and optical WDM networks. The algorithms can also be extended for their implementation on p-cycle networks.

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