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Priority-based Routing and Wavelength Assignment with Fault Resilience in WDM based Optical Networks

A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

by

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Dedicated to

The Almighty and my parents

Abstract

Wavelength-division-multiplexing (WDM) based optical network is a promising solution to fulfill the sustained growth of data traffic volume. To promote an efficient and scalable implementation of optical technology in the telecommunications infrastructure, many challenging issues related to routing and wavelength assignment (RWA), resource utilization, fault management and quality of service provisioning must be addressed with utmost importance. The most important concern regarding RWA problem is due to its NP-hardness nature. Therefore, efficient heuristic algorithms are the possible way to tackle these difficult problems. In this direction, a large number of heuristics have been attempted by researchers to solve RWA problem. Unfortunately, these heuristics could not improve the performance of the network beyond a certain limit. The majorities of the approaches do not differentiate the connection requests and treat them the same way for RWA. In this research, we explore the possibility of prioritizing connection requests for RWA to improve network performance. Accordingly, we differentiate connection requests into different priority groups based on some criteria for improving the performance. This dissertation makes important contributions to the development of WDM based optical networks, concerning RWA problem, traffic grooming, network survivability and quality of service provisioning. Contributions of this dissertation can be categorized to address four issues.

In the first contribution, we have provided the solution for reducing the affect of wavelength continuity constraint during RWA phase with incorporation of prioritization concept. The main objective in this work is to reduce the call blocking while maintaining the congestion level in the network. In this work, connection requests have been served for lightpath establishment according to their priority order. The priority order of each connection request is estimated based on the types of path (direct link physical path or indirect link physical path) and the volume of traffic. Using these criteria, direct link connection requests are always given higher priority compared to connection requests having indirect links.

We have incorporated traffic grooming mechanism with RWA approach to enhance the effective channel utilization of a given capacity optical network using less electrical-optical-electrical conversions. This has been achieved by initially multiplexing a number of low-speed connection requests which belong to same source-destination pairs. This work is our second contribution.

In the third contribution we have addressed the development of a Quality of Service (QoS) provision scheme for WDM based optical networks. We have observed from the literature survey that conventional RWA approaches do not take care of quality of service in terms of signal quality which is a critical design issue for WDM based optical networks. Therefore, we have developed a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme to reduce the total dispersion in the network, without using any dispersion compensation devices. As a result, the overall signal quality (Q-factor) has been improved without substantial increase in network setup cost. This has been achieved by assigning connection requests to wavelengths based on lightpath distance, where connection requests with longer lightpath are assigned the wavelength having lesser dispersion and vice versa.

Finally, we have incorporated a fault resilience scheme with PDRWA scheme to improve the network reliability while maintaining a better utilization of network resources. To improve network reliability, established connections with higher reliability requirement have been protected using proposed reliable shared protection algorithm and ordinary connections, that is connections without extra reliability requirement have been protected by shared protection algorithm for a better utilization of network resources. Extensive simulation studies have been carried out to evaluate the overall performance of the methods developed throughout this dissertation and compared their results with similar schemes from the literature.

Keywords: WDM, Priority, RWA, Lightpath, Virtual topology, Congestion, Traffic grooming, Dispersion, Q-factor, Reliability, Protection

Declaration

I certify that

- The work contained in the dissertation is original and has been done by myself under the general supervision of my supervisors.
- The work has not been submitted to any other Institute for any degree or diploma.
- I have followed the guidelines provided by Tezpur University in writing the thesis
- I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the university.
- Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the dissertation and giving their details in the references.

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All helps received by him from various sources have been duly acknowledged. No part of this thesis has been submitted elsewhere for award of any other degree.

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Bijoy Chand Chatterjee

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Glossary of Terms

Add-drop	Add-drop Multiplexer
AR	Adoptive Routing
ASE	Amplified Spontaneous Emission
AST	Average Setup Time
ATM	Asynchronous Transfer Mode
BFPT	Breadth-first Protection Tree
BP	Blocking Probability
BUP	Backup Path
DCF	Dispersion Compensative Fiber
DFA	Doped Fiber Amplifier
DLE	Dynamic Lightpath Establishment
DMUX	Demultiplexer
DP	Dedicated Protection
EDFA	Erbium Doped Fiber Amplifier
EL	Electrical Level
ESCON	Enterprise Serial Connection
FAR	Fixed Alternate Routing
FDDI	Fiber Distributed Data Interface
FDM	Frequency Division Multiplexing
FF	First-fit
FR	Fixed Routing
FWM	Four Wave Mixing
ILP	Integer Linear Programming
IP	Internet Protocol
ITU	International Telecommunication Union
LCR	Least Congested Routing
LED	Light Emitting Diode
LI	Linear Impairment
LL	Least-loaded
LR	Line Rate

LU	Least-used
MD	Material Dispersion
MP	Min-product
MRU	Maximizing Resource Utilization
MS	Max-sum
MST	Maximizing Single-hop Traffic
MU	Most-used
MUX	Multiplexer
NDRWA	Non Dispersion-reduced Wavelength Assignment
NLI	Non Linear Impairment
NP	Nondeterministic Polynomial
NPRWA	Non Priority-based Routing and Wavelength Assignment
NQFRW	Non QoS-aware Fault Resilience Wavelength Assignment
NSFNET	National Science Foundation Network
O/E/O	Optical-electrical-optical
OADM	Optical Add-drop Multiplexer
OC	Optical Carrier
OL	Optical Level
OR	Overhead Rate
OSC	Optical Supervisory Channel
OSI	Open Systems Interconnection
OSNR	Optical-signal-to-noise-ratio
OXC	Optical Cross-connect
PDM	Packet Division Multiplexing
PDRWA	Priority-based Dispersion-reduced Wavelength Assignment
PMD	Polarization Mode Dispersion
PP	Primary Path
PQ	Priority Queue
PRWA	Priority-based Routing and Wavelength Assignment
Q-factor	Quality Factor
QFRWA	QoS-aware Fault Resilience Wavelength Assignment
QoS	Quality-of-service
RBD	Reliability Block Diagram
RCL	Relative Capacity Loss
RSP	Reliable Shared Protection
RWA	Routing and Wavelength Assignment
RX	Receiver
SBS	Stimulated Brillouin Scattering

SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SE	SDH Equivalent
SIF	Step Index Fiber
SLE	Static Lightpath Establishment
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Networking
SP	Shared Protection
SPE	Synchronous Payload Envelope
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
STM	Synchronous Transport Module
STS	Synchronous Transport Signal
TC	Time Complexity
TDM	Time Division Multiplexing
TOSW	Thermo-optic Switch
TX	Transmitter
WA	Wavelength Assignment
WD	Waveguide Dispersion
WDDM	Wavelength Division Demultiplexing
WDDMs	Wavelength Division Demultiplexers
WDM	Wavelength Division Multiplexing
WDMs	Wavelength Division Multiplexers
WR	Wavelength Router
WWW	World Wide Web
XPM	Cross Phase Modulation

Symbols and Notations

$\alpha_{i,j}$	Total amount of traffic offered onto a lightpath from node i to node j
$\alpha_{i,j}^{s,d}$	Component of traffic offered onto a lightpath due to source-destination pair from node i to node j
β	Propagation constant
Δf_{el}	Electrical bandwidth
Δf_{opt}	Optical bandwidth
λ	Wavelength
σ_λ	Spectral width
σ_0	Pulse width
a'	Radius of the core
A_s	Amplification span
B	Channel bit rate
$B(r_i^{s,d})$	Bandwidth requirement of connection request, $r_i^{s,d}$
$B(gr^{s,d})$	Bandwidth requirement of groomed connection request, $gr^{s,d}$
$B^{s,d}$	Maximum bandwidth requirement of a connection between source-destination pair
b_i, a_i	Constants related to material oscillator strengths and oscillator wavelengths
c	Speed of light in vacuum
C_B	Maximum bandwidth of a channel
d	The destination of a connection request
$D(\lambda)$	Coefficient of total dispersion of a wavelength
D_{in}^v	Virtual in-degree
D_{matrix}	Distance matrix
D_{out}^v	Virtual out-degree
D_{PMD}	Fiber PMD coefficient
$D_{wd}(\lambda)$	Coefficient of waveguide dispersion of a wavelength
$d_{x,y}$	Distance between node x and node y

d_k	Fiber length of the k^{th} hop
$D_m(\lambda)$	Coefficient of material dispersion of a wavelength
E	Total number of links in the network
E''	Set of directed virtual links in the network
E'	Set of bi-directional optical links in the network
EOP	Power penalty due to dispersion
EOP_{PMD}	Power penalty due to PMD
$EXTP$	Extinction ratio penalty
FL	Fiber length
f_{max}	Congestion in the network
f_p	Failure rate of each primary path
f_s	Failure rate of each backup path
G''	Virtual topology
G'	Physical topology
GR	Ordered set of groomed connection requests
$gr^{s,d}$	Groomed connection request between source-destination pair
GR_1	Ordered set of groomed connection requests having direct physical link
GR_2	Ordered set of groomed connection requests having indirect physical link
$gr_{D,i}^{s_i,d_i}$	The i^{th} groomed connection requests in GR_1
$gr_{I,i}^{s_i,d_i}$	The i^{th} groomed connection requests in GR_2
$h_{i,j}^{p}$	Number of physical hop in a lightpath from node i to node j
$h_{i,j}$	Virtual hop distance
H_{matrix}	Hop matrix
K	Total number of lightpaths for a connection request
L	Total number of physical links between a source-destination pair
$l^{x,y}$	Link indicator
L_1	Length of the longest fixed route for any node pair
L_2	Length of the longest candidate route for any node pair
L_3	Hop count of the longest candidate route
N	Total number of nodes in the network
N'	Total number of spans
$N_R^{RSP}(t)$	Average reliability in the network using RSP technique for a time period, t

$N_R^{SP}(t)$	Average reliability in the network using SP technique for a time period, t
N_{PMD}	Total PMD in the network
n_1	Refractive index of the core
n_2	Refractive index of the cladding
N_D	Coefficient of total dispersion in the network
N_L	Coefficient of total fiber loss in the network
N_Q	Overall signal quality (Q-factor) in the network
$N_R(t)$	Average reliability in the network for a time period, t
NF	EDFA noise factor
$P_{x,y}^{i}$	Lightpath-link-indicator and its value is 1, if there exists a lightpath from node x to y. Otherwise its value is 0
$P_{i,j,\lambda}$	Lightpath-wavelength indicator and its value is 1, if there exists a lightpath from node i to node j and it is assigned to wavelength λ. Otherwise its value is 0
$P_{i,j,\lambda}^{x,y}$	Lightpath-wavelength-link indicator and its value is 1, if there exists a lightpath from node i to node j and it uses wavelength λ on a physical link from node x to node y. Otherwise its value is 0
$P_{i,j}$	Lightpath indicator and its value is 1, if there exists a lightpath from node i to node j. Otherwise its value is 0
P_{in}	Amplifier input power
P_s	Total span loss
$Q_{withPMD}$	Quality of signal (Q-factor) with PMD effect
$Q_{withoutPMD}$	Quality of signal (Q-factor) without PMD effect
Q_j	Q-factor of a connection, j
R	Set of all connection requests
r	A connection request
$R_{s,d}^{RSP}(t)$	Reliability of a connection using RSP technique for a time period, t
$R_{s,d}^{SP}(t)$	Reliability of a connection using SP technique for a time period, t
R_1	Reliability of a primary path
R_2	Reliability of a backup path
$R_i(t)$	Reliability of component, i for a time period, t
s	The source of a connection request
$t^{x,y}$	Average traffic flow from node x to node y
T_{matrix}	Traffic matrix
T_B	Bit duration

t_H	Holding time of a connection request
t_w	Source spectral line-width
U	Total number of groomed connection requests in the network having in-direct physical link
V''	Set of virtual links in the network
V'	Set of nodes in the network
$Vol(gr_{D,i}^{s_i,d_i})$	Volume of traffic for the groomed connection request of $gr_{D,i}^{s_i,d_i}$
W	Total number of wavelengths per fiber link
W''	Ordered set of wavelengths per fiber link
X	Total number of groomed connection requests in the network having direct physical link
Y	Total number of groomed connection requests in the network
Z	Total number of connection requests in the network

Chapter 1

Introduction

The rapid growth in world-wide communications and proliferating use of Internet has significantly modified the ways of life. This revolution has led to vast growth of communication bandwidth in every year as depicted in Figure 1-1. It can be observed from the figure that the used international bandwidth in 2002 was 1.4 terabits per second, it steadily climbed to 6.7 terabits in 2006 and has now reached 92.1 terabits per second. TeleGeography [1] expects that number to hit 606.6 terabits per second in 2018 and 1,103.3 terabits per second in 2020. At the same time, the quick evolution of optical communication technologies has allowed the transmission of vast quantities of information on a single optical fiber. However, the communication protocols adopted by telecommunication service providers have proved to be quite inefficient to exploit the enormous information carrying capacity of the emerging next-generation optical networks, which need further research initiatives.

The goal of this chapter is to briefly introduce the wavelength division multiplexing (WDM) based optical networks and describe the problems addressed by this research. The proposed solutions and their innovative aspects are briefly described to highlight the main contributions of this dissertation.

1.1 Introduction to Optical Network

To fulfill our ever-increasing bandwidth demand, all optical backbone networks along with WDM technology are essential, this is due to their many desirable properties including higher bandwidth availability, low signal attenuation, low signal

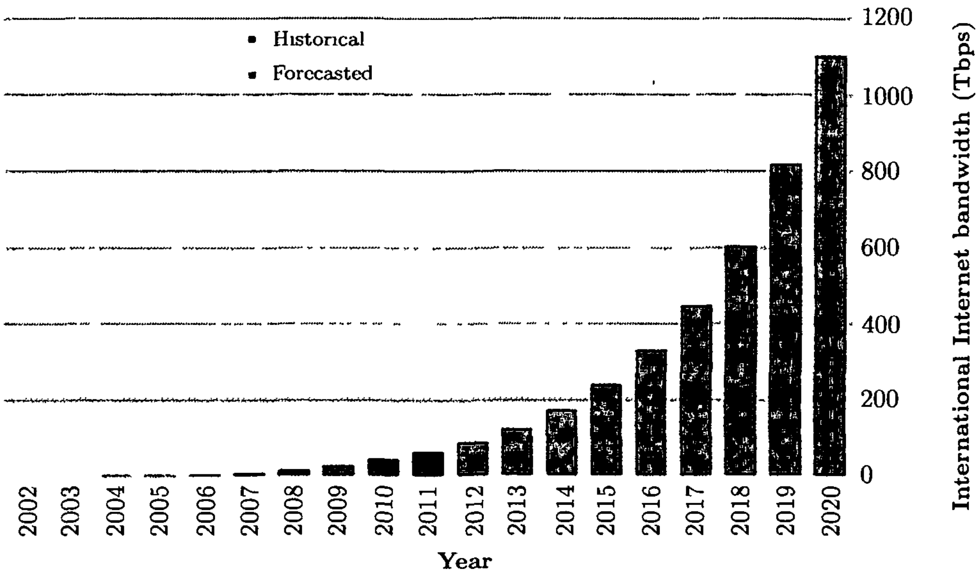

Figure 1-1: Used international internet bandwidth, 2002-2020 [1]

distortion, low power requirement, low material usage, small space requirement, and low cost WDM technology provides enormous bandwidth in optical fiber by allowing simultaneous transmission of traffic on many non-overlapping channels (also called wavelengths). In WDM based optical networks, data is converted to photons and transmitted through the fiber. Therefore, optical networks are faster compared to traditional copper wire based networks. In late 1980s, varieties of optical networks, namely, Enterprise Serial Connection (ESCON) [3], Synchronous Optical Networking (SONET) / Synchronous Digital Hierarchy (SDH) [4], Fiber Distributed Data Interface (FDDI) [5], Token-ring [6] and Ethernet [7] had been developed as a replacement of copper cable to achieve higher communication bandwidth. Among those networks, SONET/SDH had provided the basis for current high-speed backbone networks. It has also been considered to be one of the most successful standards in the entire networking industry. We briefly discuss about the SONET technology as follows.

SONET / SDH

Synchronous optical networking or synchronous digital hierarchy [8] is a standardized protocol that transfers multiple digital bit streams over optical fiber using lasers or highly coherent light from Light-emitting Diodes (LEDs). It can provide support for the operations, administration, and maintenance (OAM) functions that are required to operate digital transmission facilities. SONET has defined a hierarchy of signals called Synchronous Transport Signals (STSs). These levels are known as Synchronous Transport Modules (STMs). The physical links that transmit each level of STS are called optical carriers (OCs). The optical carrier equivalent to STS-1 is OC-1, which supports a data rate of 51.84 Mb/s. Table 1.1 [9] provides the hierarchy of the most common SONET / SDH data rates. A typical SONET transmission system consists of a transmission path and devices as depicted in Figure 1-2. In this figure, STS multiplexers and demultiplexers perform the task of multiplexing of several incoming signals onto single trunk and vice versa. Add-drop multiplexers are used in SONET technology to add signal and remove a required signal from the data stream without demultiplexing the entire signal. SONET consists of four functional layers, namely, (i) photonic layer, (ii) section layer, (iii) line layer and (iv) path layer. Photonic layer communicates to the physical layer of Open System Interconnection (OSI) model which is concerned with transmission of optical pulses. The section layer deals with signals in their electrical form It also handles framing, scrambling, and error control. The line layer is concerned with multiplexing and demultiplexing of signals. The path layer handles the transmission of a signal from source to destination. Figure 1-3 shows an STS-1 frame consisting of 6,480 bits. It is organized into 9 rows and each row contains 90 bytes The first three rows and last six rows of first three columns are used for section overhead and line overhead respectively. The rest of the frame is called the Synchronous Payload Envelop (SPE) which contains user data.

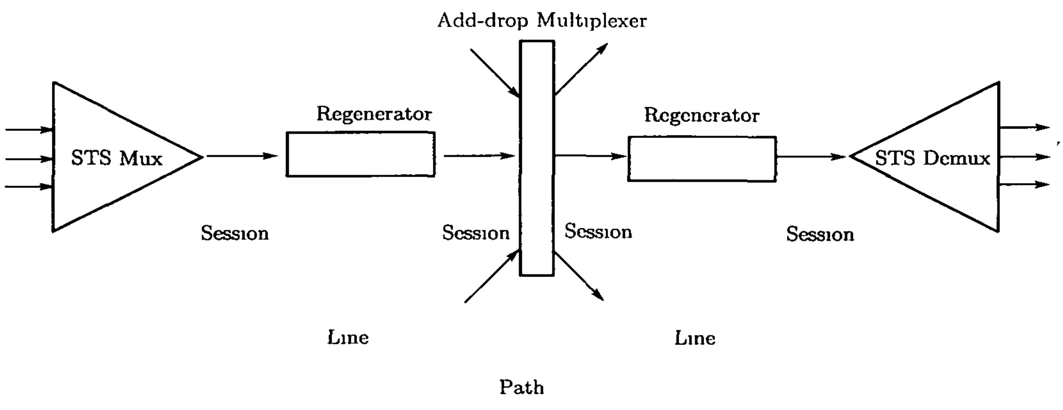

Figure 1-2: Concept of SONET system

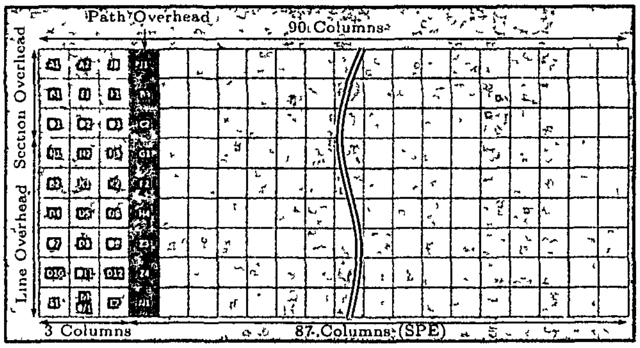

Figure 1-3: SONET STS-1 frame format [2]

Table 1.1: SONET / SDH digital hierarchy

OL	EL	LR	PR	OR	SE
OC-1	STS-1	51.840	50.112	1.728	-
OC-3	STS-3	155 520	150 336	5.184	STM-1
OC-12	STS-12	622 080	601.344	20 736	STM-4
OC-48	STS-48	2488.320	2405.376	82.944	STM-16
OC-192	STS-192	9953 280	9621 504	331.776	STM-64
OC-768	STS-768	39813.120	38486.016	1327.104	STM-256

OL Optical Level, EL Electrical Level, LR Line Rate (Mbps), PR Payload Rate (Mbps), OR Overhead Rate (Mbps), SE SDH Equivalent

1.1.1 Optical Network Architecture

The architecture of optical networks are being mainly classified into two categories, namely, (i) broadcast-and-select optical networks and (ii) wavelength-routed optical networks The following subsections briefly explain these networks

1.1.1.1 Broadcast-and-select Optical Networks

Broadcast-and-select optical networks [8, 10, 11] consist of a number of nodes. These nodes are connected through optical fibers to a passive star coupler Figure 1-4 shows a passive-star-based local optical network. In broadcast-and-select optical networks, nodes are equipped with fixed or tunable transmitters to transmit signals on different wavelengths These signals are combined into a single signal by the passive star coupler. Then, this combined signal is broadcasted to all the nodes in the network The power of transmitted signal is split equally among all the output ports leading to all nodes in the network Each node can select a required wavelength to receive the desired signal by tuning its receiver to that wavelength The communication between transmitter and receiver can be classified into two categories, such as (i) single-hop communication and (ii) multi-hop communication. In single-hop communication, transmitted signals travel from source to destination entirely in optical domain. Multi-hop communication transmits the signal through a certain number of wavelengths and thus forms a virtual path over the physical path.

The broadcast-and-select network can easily support multi-cast traffic Therefore, multiple receivers at different nodes can be tuned to receive the same wavelength. The main drawbacks of broadcast-and-select network are as follows - (i) it requires synchronization and rapid tuning, (ii) it cannot support wavelength reuse characteristic and hence a large number of wavelength channels is required, (iii) the signal power is split among various nodes, therefore this type of network cannot be used in long distance communication. Mostly broadcast-and-select optical network is being used in high-speed local area networks and metropolitan area networks.

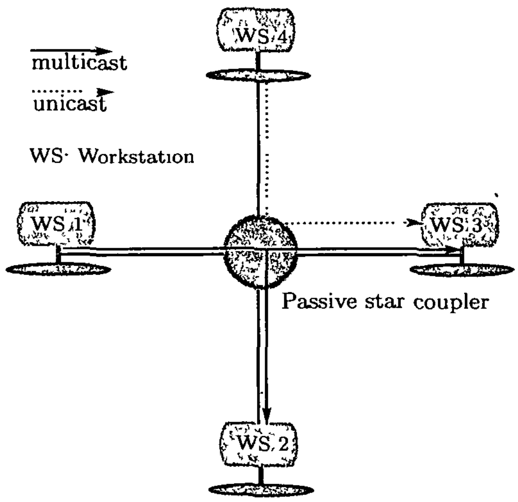

Figure 1-4: A passive-star-based local optical network

1.1.1.2 Wavelength-routed Optical Networks

Wavelength-routed optical network [8, 10, 12] is being designed to overcome the problems of broadcast-and-select network. Wavelength-routed optical network has the potential to solve the problems, mainly (i) lack of wavelength reuse, (ii) power splitting loss and (iii) scalability of wide-area network. A wavelength-routed network consists of routing nodes which are interconnected by fiber links. Each node is equipped with a set of transmitters and receivers for sending and receiving data. In wavelength-routed optical network, end users communicate with one another via all-optical WDM channels, which are referred to as lightpaths [8, 10]. Although use of wavelength converters in an optical network may increase the number of established lightpaths, but they still remain very expensive. Furthermore, uses of wavelength converters introduce extra traffic delay in the network. Therefore, most of the research in WDM based optical network focuses mainly on without wavelength conversion. In the absence of wavelength converters, the same wavelength must be used on all hops in the end-to-end path of a connection. This property is known as wavelength continuity constraint [8, 10]. Figure 1-5 shows the establishment of lightpaths between source-destination pairs on different wavelengths in an example wavelength routed optical network. For the same network, the established lightpaths between source-destination pairs are shown in Table 1.2. In the figure, each lightpath uses the same wavelength on all hops in the end-to-end path due to wavelength continuity constraint property. The established lightpaths between source-destination pairs A-C and B-F use different wavelengths λ_1 and λ_2, because they use the common fiber link 6-7. This property is known as distinct channel constant [8, 10]. The established lightpaths between source-destination pairs H-G and D-E use the same wavelength λ_1 which is already used by the lightpath A-C due to a wavelength reuse characteristic. Given a set of connection requests to be served by the WDM system, the problem of establishment of lightpaths for each connection request by selecting an optimal route and assigning a required wavelength is known as Routing and Wavelength Assignment (RWA) problem [8, 10]. Our research work is based on routing and wavelength assignment problems in wavelength-routed WDM based optical network. Therefore, the detail functionality of routing and wavelength assignment will be discussed in the following chapters.

Table 1.2: Summaries of established lightpaths.

S-D pair	Used Wavelength	Lightpath
A-C	λ_1	A-1-6-7-C
B-F	λ_2	B-6-7-8-4-F
H-G	λ_1	H-2-3-G
D-E	λ_1	D-10-9-E

A WDM based wavelength-routed optical network [10] has mainly three layers, namely, (i) physical layer, (ii) optical layer and (iii) client layer. Figure 1-6 shows all the possible layers in a WDM based wavelength-routed optical network which are discussed below.

(a) **Physical layer**: Physical layer is the lowest layer of an optical network. It is designed to meet the traffic demand, utilize the network resources efficiently

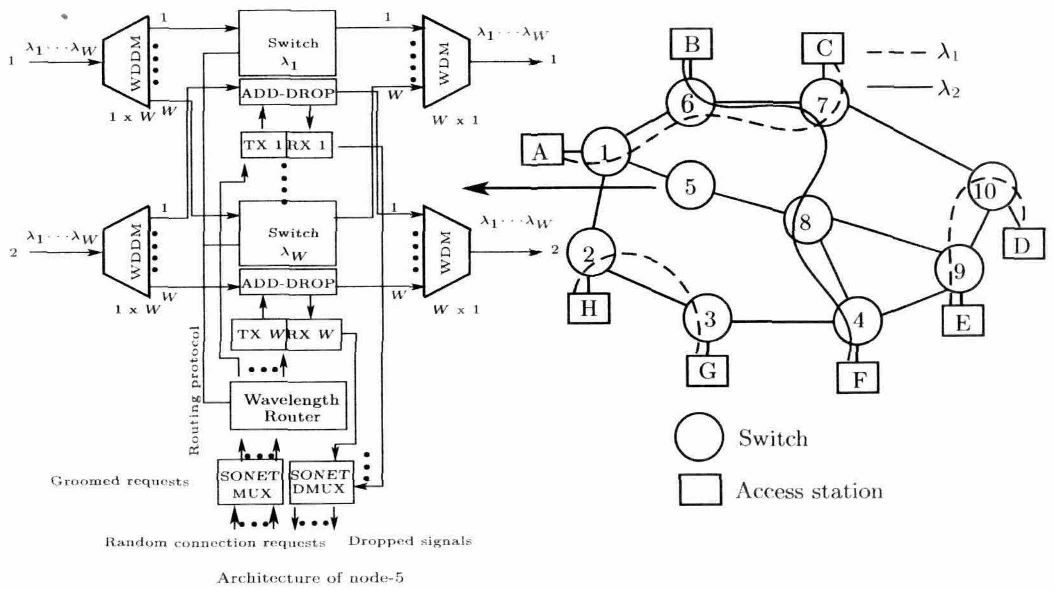

Figure 1-5: A wavelength-routed optical network

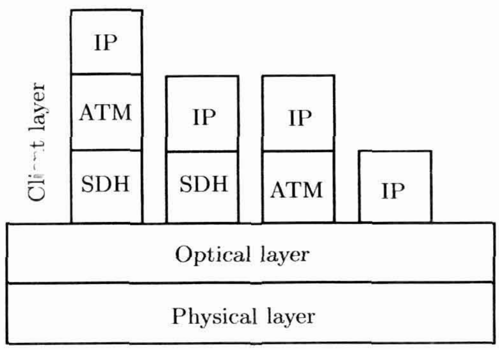

Figure 1-6: Layers of a WDM based wavelength-routed optical network

and provide quality of service to the end-users.

(b) **Optical layer**: Optical layer is the middle layer, between the lower physical and upper client layers. Optical layer provides lightpaths to the client layers. These lightpaths are the physical links between client layer network elements. This layer also provides the client independent or protocol transparent circuit-switched service to variety of clients. Therefore, the optical layer can support variety of clients simultaneously, for an example, some lightpaths may carry ATM cells, whereas others may carry SONET data or IP packets/datagrams. WDM based optical network with an optical layer can be configured in such a way that if any failure occurs, the signal can be transmitted using alternate paths automatically. Thus, the reliability of this type of network is higher compared to traditional network. An optical layer can be further decomposed into three sub layers: (i) optical channel layer, (ii) optical multiplex section layer and (iii) optical transmission section layer. The functionality of an optical channel layer is to provide end-to-end networking of optical channels or lightpaths for transparently conveying the client data. Optical multiplex section layer aggregates low speed multi wavelength optical signals. An optical transmission section layer concerns with the transmission of optical signals on different kinds of optical media such as single-mode and multi-mode transmission.

(c) **Client layer**: The most common protocols of client layer are SONET/SDH, Ethernet and ATM, which are being used to communicate with end-users. The detailed descriptions of these protocols can be found in [13].

1.1.2 Principles of Optical Fiber

An optical fiber consists of a very fine cylinder of glass called core which is used to propagate light pulses. Figure 1-7 shows the physical structure of an optical fiber. In the figure, the core is surrounded by a concentric layer of glass called cladding. Core and cladding are protected by a thin plastic jacket. The refraction index of core, n_1 is greater than that of the cladding, n_2. When a ray of light crosses a boundary between materials with different kinds of refractive indices, the ray of light is partially refracted at the boundary surface and partially reflected. However, if the angle of incidence is greater than that of critical angle[1] [10], the ray of light totally reflected back internally. The reflection and refraction of light pulse are depicted in Figure 1-8. Total internal reflection theorem has been used in optical fiber to propagate the optical signal from transmitter to receiver.

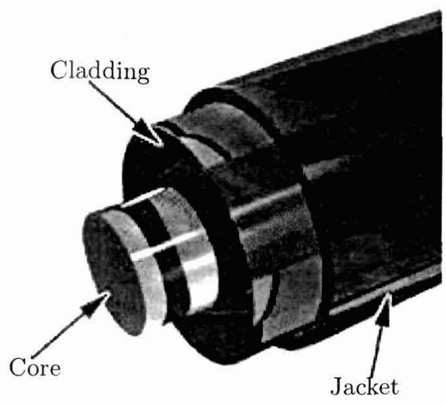

Figure 1-7: Physical structure of an optical fiber

[1] is defined as the angle of incidence that provides an angle of refraction of 90-degrees.

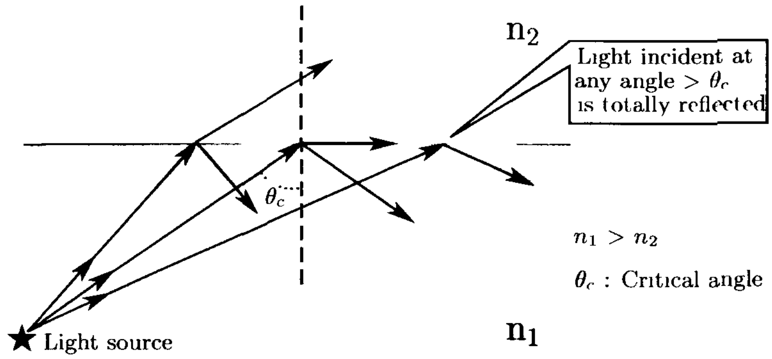

Figure 1-8: Reflection and refraction of light pulse

1.1.3 Optical Transmission System

A typical optical transmission system has three basic components, namely, (i) transmitter, (ii) transmission medium, and (iii) receiver. Transmitter is used to convert data into a sequence of on/off light pulses. These light pulses are transmitted through the transmission medium and finally, converted back to the original data at the receiver side. An optical transmitter is essentially a light source. Although, initially LEDs had been used as a light source but nowadays, all optical networks use lasers to produce high-powered beams of light. Optical fiber has been used as a transmission medium in optical communication systems. Normally, photodiode can be used as a receiver to convert a stream of photons (optical signal) into a stream of electrons (electrical signal). It has been observed that when a light pulse propagates through optical fiber, it is distorted This distortion occurs mainly due to physical layer impairments [14]. Physical layer impairments can be classified into two categories, namely, (i) Linear Impairments (LIs) and (ii) Non-linear Impairments (NLIs), which are discussed in the following subsections.

1.1.3.1 Linear Impairments

The most important linear impairments for signal distortion are signal attenuation and dispersion. Signal attenuation [15] in fiber leads to loss of signal power due to impurities in the fiber glass and Rayleigh scattering [15]. Signal attenuation is measured in decibels as 10 $log_{10}(transmitted\ power/received\ power)$. Figure 1-9 shows the attenuation in decibels per kilometer of fiber for different wavelengths. From the figure, it can be observed that three main low-loss band centered at

0.850, 1.300 and 1.550 micron. Among these bands, C band (1.530-1.565 micron) and L band (1.565-1.625 micron) have been usually used to achieve huge communication bandwidth due to lower attenuation. To overcome attenuation, repeaters are placed to restore the degraded signal for continuing further transmission.

On the other hand, when the light pulses propagate through optical fiber, the pulses spread out (*i.e.*, duration of the pulses broaden). This spreading of light pulses is called dispersion [15]. Dispersions in optical fiber are mainly classified into three categories, namely, (i) Material Dispersion (MD), (ii) Waveguide Dispersion (WD) and (iii) Polarization Mode Dispersion (PMD). MD occurs due to the refractive index which varies as a function of the optical wavelength. WD is caused by the wavelength dependence of the group velocity due to specific fiber geometry. It describes the dependence of the effective refraction index on the normalized frequency of radiation propagating through the optical fiber. The waveguide dispersion results in distribution changes of power between the core and the cladding. PMD is a form of modal dispersion, where different polarizations of optical signal travel with different group velocities due to random imperfections and asymmetries. PMD plays an important role in higher bit rate channel greater than or equal to 10 Gbps. Although, dispersion compensating devices like - dispersion compensating fiber, optical phase conjugation, pulse prechirping and duobinary transmission have been usually used to reduce dispersion, they are very expensive. The effects of these linear impairments will be discussed in chapter 5.

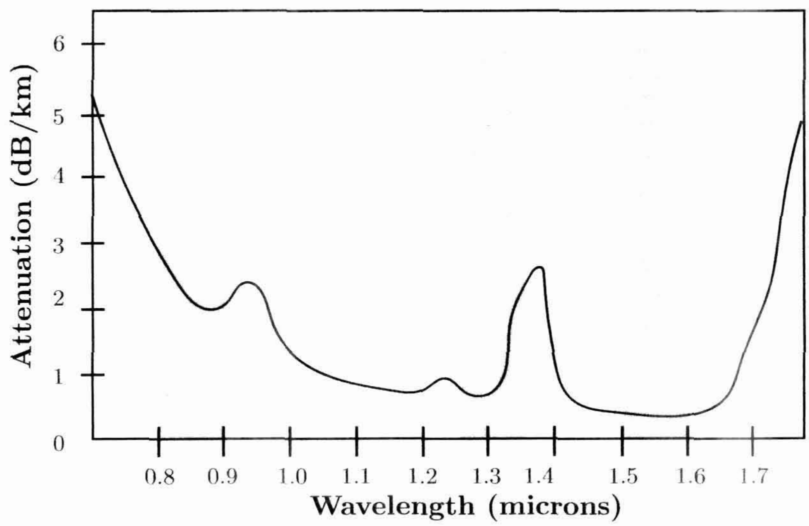

Figure 1-9: Attenuation versus wavelength for optical fiber

1.1.3.2 Non-linear Impairments

The non-linear effects in optical fiber occur either due to change in the refractive index of the medium with optical intensity (power) or due to inelastic-scattering phenomenon. The important non-linear impairments are: (i) Self Phase Modulation (SPM), (ii) Four Wave Mixing (FWM). (iii) Cross Phase Modulation (XPM), (iv) Stimulated Brillouin Scattering (SBS) and (v) Stimulated Raman Scattering (SRS). These effects are out of the scope of this dissertation. and a description of these phenomena can be found in [14].

1.1.4 Wavelength Division Multiplexing

An optical fiber has an enormous bandwidth capacity, but the accessing rate of end-user (for example. a workstation) is limited which is a few gigabits per second. Therefore, it is extremely difficult to exploit all the huge communication bandwidth of a single fiber using a single wavelength channel due to optical-electronic bandwidth mismatch. Wavelength Division Multiplexing (WDM) [8,10] is a technique that can manage the huge opto-electronic bandwidth mismatch by multiplexing wavelengths of different frequencies onto a single fiber as shown in Figure 1-10. WDM creates many virtual fibers and each of them can capable of carrying a different signal. Each signal can be carried at a different rate like - OC-3/STM-1. OC-48/STM-16, and so on and in a different format, such as, SONET/SDH, ATM, data, and so on. Therefore, the capacity of existing networks can be improved using the WDM technology, without upgrading the network.

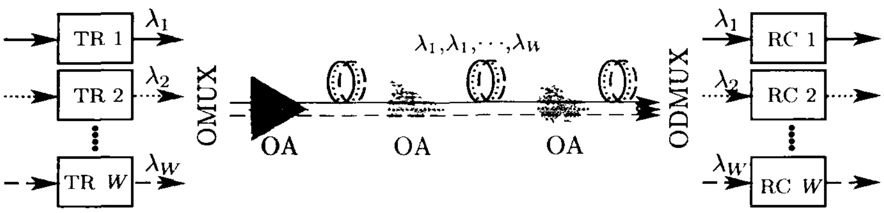

Figure 1-10: Concept of wavelength division multiplexing

1.1.5 Basic Components of WDM based Optical Networks

In this section, we briefly discuss about various major components [8,10,12,15–17] which are the building blocks of WDM based optical networks. We discuss only the major components because the innovations in optical components are still on-going.

(a) **Optical Multiplexer and Demultiplexer**: Optical multiplexer and demultiplexer are the key components in WDM based optical networks. Optical multiplexer and demultiplexer are used to integrate and divide wavelengths of different frequency in fibers. A wide range of techniques [12, 16] have been applied to realize the functionality of optical multiplexer and demultiplexer.

(b) **Optical Fiber**: Optical fiber is a flexible and transparent fiber. It is made of glass, and it acts as a waveguide to transmit light pulses from sender to receiver. Optical fibers have been classified into multi-mode and single-mode fibers. The cross sections of both multimode and single mode optical fibers are shown in Figure 1-11. Total internal reflection theorem of light is being applied to propagate signal from transmitter to receiver, which is already explained in section 1.1.2.

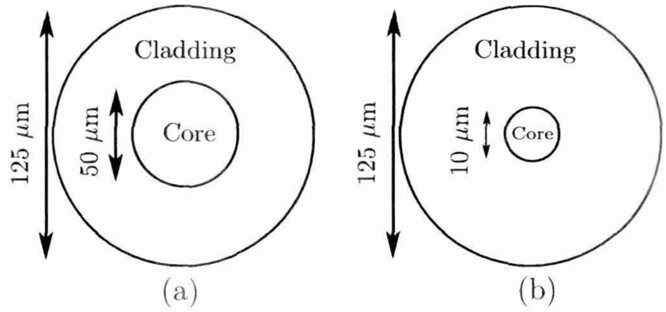

Figure 1-11: Cross sections of (a) multimode and (b) single mode fibers

(c) **Optical Transmitter**: An optical transmitter is a device that accepts an electrical signal as its input, processes this signal, and produce an optical signal capable of being transmitted through an optical transmission medium. Two major types of optical transmitters [15] are available, namely, (i) LED and (ii) laser. Normally, transmitted powers from LEDs are lower than that of lasers, but LED transmitters are cheaper and less sensitive. Hence, in low-performance systems, LEDs are preferred, but nowadays almost all optical networks use lasers to produce high powered beams of light.

(d) **Photodetector**: Photodetector is an optoelectronic device which absorbs optical energy and converts it to electrical energy. It has the following properties: (i) it is insensitive to variations in temperature, (ii) it is compatible

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with the physical dimensions of the optical fiber, (iii) it has a reasonable cost compared to other components of optical communication system and (iv) it has a long operating life. Several types of photodetector, namely, (i) photomultiplier, (ii) pyroelectric detector, (iii) semiconductor-based photoconductor, (iv) phototransistor and (v) photodiode have been used in optical communications and the working principles of these photodetectors can be found in [15].

(e) **Optical Coupler / Splitter**: Optical coupler / splitter [15] is used to combine and split signals in optical domain. Normally, an N x M coupler has N inputs and M outputs. Figure 1-12 shows a 2 x 2 coupler which can be fabricated by twisting together, melting, and pulling two single mode fibers. As a result, they get fused together over a uniform selection of length. In the figure, each input and output fiber has a long tapered section of length. This is because, the transverse dimensions are gradually reduced down to the coupling region. In Figure 1-12, P_0, P_1, P_2, P_3 and P_4 are the input power, throughout power, power coupled into the second fiber, low level signal (-50 to 70 dB below the input level) and scattering, respectively. The low level signal, P_3 is caused from backward reflections and the scattering, P_4 is generated due to bending and packaging of the device.

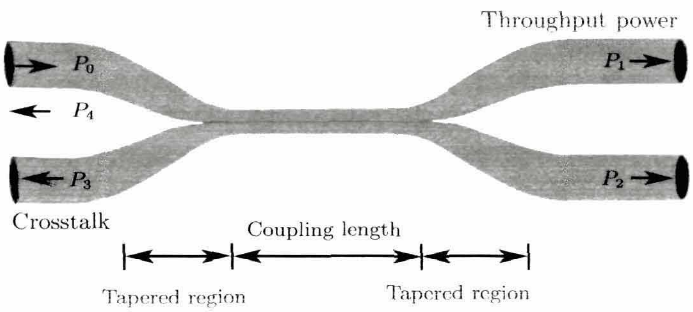


Figure 1-12: 2 x 2 optical coupler

(f) **Optical Amplifier**: Optical amplifier [15] is used to amplify optical signal without converting it to an electrical signal. It can be classified into two categories, namely, (i) Doped Fiber Amplifier (DFA) and (ii) Semiconductor Optical Amplifier (SOA). The general applications of the following three classes of optical amplifiers are shown in Figure 1-13.

- **In-line optical amplifier**: In single mode fiber, the effect of dispersion is less, but the main limitation is fiber attenuation. Therefore, in-line optical amplifier has been used to compensate the power loss and hence the distance between repeater stations is increased.

- **Preamplifier**: Preamplifier is used to amplify weak optical signal before photodetection. Therefore, the signal-to-noise ratio degradation caused by thermal noise in the receiver can be suppressed.
- **Power amplifier**: Power amplifier is placed immediately after the optical transmitter to boost the transmitted power.

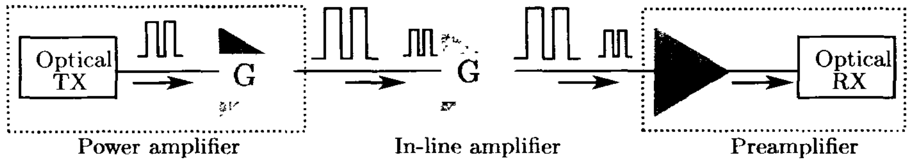


Figure 1-13: Applications of optical amplifiers

(g) **Tunable Filter**: Optical filters are dynamically tunable over a certain optical frequency band. They have been used to increase the flexibility of WDM based optical networks. The working principles of tunable optical filter can be found in [18].

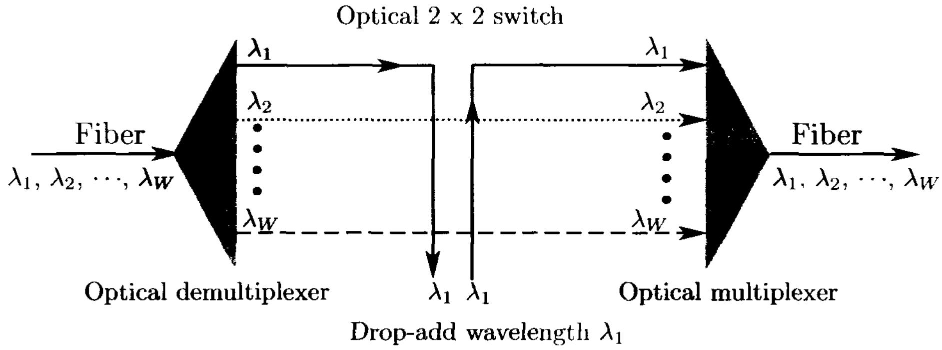


Figure 1-14: Optical add-drop multiplexer

(h) **Optical Add-drop Multiplexer**: Optical add-drop multiplexer (OADM) [15] is used in WDM based system for multiplexing and routing different wavelengths into or out of a fiber. This device can add one or more new wavelength channels to an existing multi-wavelength signal. It can also drop (remove) one or more channels from the passing signals to another network path. OADMs are classified as - (i) fixed-wavelength OADM and (ii) dynamically wavelength selectable OADM. In fixed-wavelength OADM, the wavelength that is being selected remains in the network until it is changed. But in case of dynamically selectable wavelength OADM, the wavelengths between the optical demultiplexer/multiplexer may be dynamically directed from the outputs of the demultiplexer to any of the inputs of the multiplexer.

Figure 1-14 shows the functionality of an optical drop-add multiplexer which is used to selectively remove a wavelength (*i.e.* λ_1) and add the same wavelength in the fiber.

(i) **Optical Supervisory Channel**: Optical supervisory channel (OSC) [15] is a separate wavelength/channel, usually placed outside the amplification band (at 1310 nm, 1510 nm and 1620 nm). It carries information about the multi-wavelength optical signal as well as remote information of the optical terminal for network management purposes.

(j) **Wavelength Cross-connect**: Optical cross-connect (OXC) is used to switch optical signals from input ports to output ports. It has been also considered to be wavelength insensitive (*i.e.*, incapable of demultiplexing of different wavelength signals on a given input fiber). Normally, cross-connect element is a 2 x 2 cross-point element which routes optical signals from two input ports to two output ports. It has two states, namely, (i) cross state and (ii) bar state, shown in Figure 1-15. In the cross state, the signal from the upper input port is routed to the lower output port and the signal from the lower input port is routed to the upper output port. But in the bar state, the signal from the upper input port is routed to the upper output port and the signal from the lower input port is routed to the lower output port.

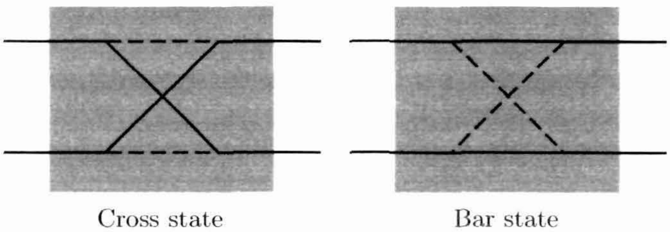


Figure 1-15: 2 x 2 crossconnect elements in the cross state and bar state

(k) **Optical Switch**: Optical switch is used in communication system to switch signal in optical fiber from one circuit to another circuit. The main considerations and aspects for building switches are - (i) number of required switch elements, (ii) loss uniformity, (iii) number of crossovers and (iv) blocking characteristics. Different types of switches, such as, crossbar, thermo-optic, clos and spanke have been used and their characteristics, architectures, pros and cons can be found in [12].

1.2 Motivation of the Research

Routing and wavelength assignment (RWA) [8, 10] is considered to be one of the key functionality for optical networks, due to its information transparency and wavelength reuse characteristics. RWA is used to select the best possible end-to-end routes and assign suitable wavelengths for connection requests. From the literature survey, it had been revealed that RWA in WDM based optical network is an NP-hard [19, 20] problem. Therefore, efficient heuristic algorithms are the best way to tackle these difficult problems. In this direction, a large number of heuristics have been attempted by researchers to solve RWA problem. Unfortunately, these heuristics could not improve the performance of the network beyond a certain limit. The majorities of the approaches do not differentiate the connection requests and treat them the same way for RWA. In this research, we explore the possibility of prioritizing connection requests for RWA to improve network performance. Accordingly, we differentiate connection requests into different priority groups based on some criteria for improving the performance. Some of the key issues and difficulties for RWA in optical networks which motivate us for this research are as follows:

- Hop-wise traffic grooming requires optical-electrical-optical (O/E/O) conversion at each hop which leads to increase in both network setup cost and traffic delay.
- Using a conventional RWA scheme under wavelength continuity constraint mostly leads to a situation where wavelengths may be available but a connection request cannot be established due to unavailability of a specific wavelength.
- To the best of our knowledge, no dispersion-reduced wavelength assignment scheme has been proposed in literature without using dispersion compensating devices to improve signal quality (Q-factor) and without substantial increase in network setup cost.
- Existing fault resilience techniques [21, 22] are unable to handle multi-failure simultaneously. Therefore, incorporating fault resilience technique with dispersion-reduced wavelength assignment scheme may improve reliability by handling multi-failure simultaneously while maintaining better utilization of network resources and better quality of signal.

1.3 Research Objective

The broad objectives of the research work are as follows:

- Designing a priority-based routing and wavelength assignment scheme
  - To reduce the affect of wavelength continuity constraint with incorporation of prioritization concept
  - To reduce the call blocking while maintaining the congestion level in the network
- Incorporating traffic grooming with routing and wavelength assignment schemes
  - To multiplex low-speed connection requests onto high capacity wavelength channels
  - To enhance the channel utilization of a given capacity optical network using lesser number of O/E/O conversions
- Designing a priority-based dispersion-reduced wavelength assignment scheme
  - To reduce the total dispersion in the network without using dispersion compensating device
  - To improve the overall signal quality (Q-factor) in the network, without substantial increase in network setup cost
- Designing a quality-of-service (QoS)-aware fault resilience wavelength assignment scheme
  - To improve network reliability by handling multiple failures simultaneously
  - To maintain better utilization of network resources

Keeping the above broad objectives in mind, the works done in this dissertation are outlined in the next section (Dissertation Contributions).

1.4 Dissertation Contributions

In this dissertation, algorithms and techniques used for RWA problem and providing resilience against failure in a WDM based optical network have been studied. The basic aim is to develop efficient algorithms, schemes for RWA problem providing performance improvements over existing algorithms and techniques. This is accompanied by development of schemes and frameworks followed by extensive experimentation to validate the claim of performance improvements. The main contributions of this dissertation can be divided into four parts. The following subsections briefly outline the major contributions of this dissertation.

1.4.1 Performance Analysis of Major Conventional RWA Approaches

In the first part of the work, we have analyzed the performance of major conventional routing algorithms (namely, fixed routing, fixed alternate routing and adaptive routing) and wavelength assignment schemes (namely, first-fit, random and least-used) in terms of blocking probability[2] and average setup time[3] [23]. In this research work, we have only considered first-fit, Random and Least-used wavelength assignment schemes due to their lower computational complexity compared to other wavelength assignment schemes. From the simulation study, it has been observed that the performance of the first-fit wavelength assignment scheme in terms of blocking probability is better than other wavelength assignment schemes. Although, adaptive routing with first-fit scheme provides the best performance in terms of blocking probability, its average setup time is very high compared to other routing algorithms. Fixed alternate routing with first-fit trades-off between blocking probability and average setup time.

Furthermore, it has been revealed that for an acceptable level of call blocking, they all require very large number of wavelength channels. This problem has been addressed in our subsequent works.

[2]defined as a ratio of total number of blocked calls and total number of connection requests in the network.

[3]defined as a ratio of total execution time which is required to establish all the connection present in the network and total number of successful connections.

1.4.2 PRWA : Priority-based Routing and Wavelength Assignment Scheme

One of the challenging issues in optical networks is reducing call blocking. Call blocking increases with number of connection requests due to availability of limited number of wavelength channels in fiber links. In this part of the work, we have proposed a priority-based routing and wavelength assignment (PRWA) scheme with incorporation of a traffic grooming mechanism to reduce the call blocking while maintaining the congestion level in the network. In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate O/E/O conversion and then these groomed connection requests are served by a RWA approach according to their priority order. The priority order of each groomed connection request is estimated based on the types of path (direct link physical path or indirect link physical path) and the volume of traffic. By estimating the priority order of connection requests using these criteria, blocking of connection requests due to wavelength continuity constraints can be reduced to a greater extent. This in turn leads to a better performance of the network in terms of lower call blocking while maintaining the congestion level in the network. The performance analysis of the PRWA scheme has been conducted in terms of blocking probability and congestion. The results have been compared with a similar type of non priority-based routing and wavelength assignment (NPRWA) scheme in which first-fit [24] wavelength assignment method is used. From the simulation study, it has been observed that the PRWA scheme significantly reduces the blocking probability while maintaining the congestion level in the network, compared to NPRWA scheme.

In this work, we have investigated the RWA problem with traffic grooming for reducing call blocking. However, quality of service (QoS) is a critical design issue in WDM based optical networks to maintain the signal quality which has been addressed in the next work.

1.4.3 PDRWA : Priority-based Dispersion-reduced Wavelength Assignment Scheme

Dispersion in optical fiber degrades the quality of signal in the networks. Although, the use of dispersion compensating fiber (DCF) reduces the effects of dispersion, it is expensive and has more propagation loss compared to step-index fiber (SIF). In this part of the work, a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme for optical networks has been proposed to reduce overall dispersion in the networks, without using any dispersion compensating devices. In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate O/E/O conversion and then these groomed connection requests are assigned wavelengths based on their lightpath distance, where connection requests with longer lightpath are assigned the wavelengths having lesser dispersion and vice versa. By assigning wavelength using such constraint, the total dispersion in the network can be reduced to a greater extent. This in turn leads to a better performance of the network in terms of overall signal quality (Q-factor), without substantial increase in network setup cost. The performance analysis of the PDRWA scheme using SIF has been conducted with three different channel speeds (10, 40 and 100 Gbps) in terms of total dispersion and the results are compared with the use of DCF. We have also studied the overall Q-factor in the network with different channel speeds and considering polarization mode dispersion (PMD) effect using SIF and DCF. From the simulation study, it has been observed that the total dispersion increases with channel speed. The rate of increase of total dispersion using PDRWA scheme is less than that of using a similar type of non dispersion-reduced wavelength assignment (NDRWA) scheme in which first-fit [24] wavelength assignment method is used. As a result, the overall Q-factor in the network using the PDRWA scheme is improved compared to NDRWA scheme. Furthermore, it has been noticed that Q-factor (with PMD effect) while using PDRWA scheme with SIF has improved compared to PDRWA scheme with DCF, due to the higher PMD coefficient.

In this work, we have investigated the RWA problem with traffic grooming to improve the quality of service in terms of signal quality (Q-factor). Nowadays, survivability has become an important issue in WDM based optical networks which has been addressed in our last work.

1.4.4 QFRWA : QoS-aware Fault Resilience Wavelength Assignment Scheme

Frequent occurrences of natural disasters damage large portions of optical network, mainly optical fiber and network nodes, and therefore, the survivability has become an important and challenging issue in practical use of optical networks. In this context, at the last part of the thesis work, we have incorporated a fault resilience scheme with the RWA approach to improve the network reliability while maintaining a better utilization of network resources and a better quality of the signal (Q-factor). In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate O/E/O conversion and then these groomed connection requests are served by wavelength assignment according to a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme. Finally, the established connections with higher reliability requirement are protected using a reliable shared protection (RSP) algorithm. This is achieved by restricted sharing of the backup paths in the sub branches of the protected trees to provide more reliability for those connections. The ordinary connections, that is connections without extra reliability requirement are protected by shared protection technique for a better utilization of network resources. The performance analysis of the QFRWA scheme has been conducted to evaluate the suitability of the scheme in terms of reliability and overall signal quality in the network. We have compared the results with a similar type of non QoS-aware fault resilience wavelength assignment (NQFRWA) scheme. From the simulation study, it has been found that the QFRWA scheme improves the network reliability and maintains a better quality of signal compared to NQFRWA scheme.

1.5 Dissertation Organization

In the following, we briefly outline the organization of this dissertation.

Chapter 1: *Introduction* - This chapter gives a brief introduction to optical networks, explaining the motivation, main objectives, and summarizing the contributions of the thesis.

Chapter 2: *Literature Survey* - This chapter provides an overview of the existing works on lightpath establishment, routing, wavelength assignment, traffic grooming and fault resilience design in WDM based wavelength routed optical networks.

Chapter 3: *Performance Analysis of Major Conventional RWA Approaches* - The performance analysis of major conventional routing and wavelength assignment approaches in optical networks are presented in this chapter.

Chapter 4: *Priority-based Routing and Wavelength Assignment Scheme* - A priority-based routing and wavelength assignment scheme (PRWA) with the incorporation of a traffic grooming has been proposed in this chapter to achieve the reduction of call blocking while maintaining the congestion level in the optical networks.

Chapter 5: *Priority-based Dispersion-reduced Wavelength Assignment Scheme* - In this chapter, we propose a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme with incorporation of traffic grooming to achieve the reduction of the total dispersion in the network. As a result, the overall signal quality is improved without substantial increase in network setup cost.

Chapter 6: *QoS-aware Fault Resilience Wavelength Assignment Scheme* - In this chapter, we incorporate a fault resilience technique with PDRWA scheme to improve the reliability in the network while maintaining a better utilization of network resources and a better quality of the signal (Q-factor).

Chapter 8: *Conclusion and Future Direction* - This chapter concludes the dissertation by summarizing the basic findings and also by suggesting some future directions of further research in this area.

Chapter 2

Literature Survey

2.1 Introduction

This dissertation contributes algorithms and schemes in the area of wavelength division multiplexing (WDM) based optical networks. In this context, this chapter provides a comprehensive survey on various works done in the field of routing and wavelength assignment, recovery techniques for handling faults in WDM based optical networks. This survey will provide a strong foundation to appreciate the different schemes developed throughout this dissertation. The rest of this chapter is organized as follows. Section 2.2 discusses about the lightpath establishment problems in optical networks. Section 2.3 presents major routing problems for both static and dynamic traffic environment. In this section we also discuss about the pros and cons of different routing algorithms Section 2.4 discusses and compares various algorithms for static and dynamic wavelength assignment approaches. Traffic grooming mechanism and its pros and cons are presented in section 2.5. Section 2.6 focuses on different recovery methods and their working principle in optical networks. Further, in this section we discuss about the classification of recovery techniques Finally, section 2 7 concludes this chapter.

2.2 Lightpath Establishment

WDM based optical network has been rapidly gaining growing acceptance due to its ability to handle the ever-increasing traffic demands of network users. In a wavelength-routed WDM based optical network, end users communicate with each other via all-optical WDM channels, which are referred to as lightpaths. A lightpath is used to support a connection in a wavelength-routed WDM based network, and it may span multiple fiber links. It has been observed from the literature survey that mainly two different types of traffic assumptions [25–29] namely, (i) static traffic and (ii) dynamic traffic have been considered for routing and wavelength assignment (RWA) purpose, which are discussed below.

- In case of static traffic assumption [8,25], information about the connections are known in advance. The traffic demand may be specified in terms of source-destination pairs. These pairs are chosen based on an estimation of long-term traffic requirements between the node pairs. The objective is to find out end-to-end routes and assign wavelengths for all the traffic demand, while minimizing the number of wavelengths used.
- In case of dynamic traffic assumption [8, 28, 29], the arrival and departure of connections in the network take place one by one in a random manner. The lightpaths once established remain active for a finite amount of time before departing. The dynamic traffic demand models several situations in transport networks. Sometimes, it may become necessary to tear down some of the existing lightpaths and establish some new lightpaths in response to changing traffic patterns or network component failures.

The amount of call blocking using static traffic is more than that of using dynamic traffic. Therefore, dynamic traffic is more preferable in optical networks to minimize call blocking and to maximize the network throughput. In the following subsections, we briefly discuss about lightpath establishment using both static and dynamic traffic.

2.2.1 Static Lightpath Establishment

The establishment of lightpath using static traffic assumption is known as Static Lightpath Establishment (SLE) problem. Here, attempt is made to minimize the number of wavelengths required to setup a given set of lightpaths. In the literature, a number of studies [19, 20, 30–32] have investigated the SLE problem to establish a static set of lightpaths in optical networks. In this direction, Ramaswami and Sivarajan [31] have formulated static RWA problem as an NP-hard problem. Imrich Chlamtac *et al.* [33] have proved that the SLE problem is an NP-complete problem by formulating SLE problem as polynomial time reducible to n-graph-colorability problem. Therefore, many researchers have attempted to propose efficient heuristic algorithms [33,34] for solving static RWA problems. Although the computational complexity of the SLE problem is found to be smaller than that of dynamic lightpath establishment problem, number of blocked connections in SLE is more compared to dynamic lightpath establishment. SLE problem is often decoupled into two subproblems, namely, (i) routing and (ii) wavelength assignment for making the problem more tractable.

2.2.2 Dynamic Lightpath Establishment

The establishment of lightpath under dynamic traffic assumption is known as Dynamic Lightpath Establishment (DLE) problem. In dynamic provisioning, a lightpath is established in real-time without predetermined routes and the knowledge of future lightpath provisioning events. Here, attempt is made to choose a route and a wavelength which maximizes the probability of setting up a given connection, while minimizing the number of blocked connections. In DLE, lightpaths are established dynamically on the basis of link-state information and as a result a virtual topology[1] is formed. The established connections are no longer required after a certain amount of time and then these lightpaths are taken down dynamically. Using this criterion, on-demand lightpath establishment has been implemented in order to enable service providers to fulfill customer demands quickly and economically. It had been revealed from the literature that DLE problem is an NP-hard problem [35]. Therefore, efficient heuristic approaches are the possible ways to tacle this difficult problem. In this direction, Mondal *et al.* [35], Shen *et al.* [36], and Ramamurthy *et al.* [37] have proposed heuristic algorithms for establishing dynamic lightpaths in optical networks. Similar to SLE, DLE problem can also be decoupled into two subproblems, namely, (i) routing and (ii) wavelength assignment, which are discussed in sections 2.3 and 2.4, respectively.

2.3 Routing

Approaches for solving routing subproblem (also called routing algorithm) in optical networks can be categorized into four types, namely, (i) Fixed Routing (FR) [38], (ii) Fixed Alternate Routing (FAR) [39], (iii) Adaptive Routing (AR)

[1]The set of lightpaths established over a physical topology forms a virtual topology. The higher layer in a transport network uses the virtual topology on the optical path layer for message transmission.

[40–42], and (iv) Least Congested Routing (LCR) [43]. These routing approaches have mainly considered to find out the suitable end-to-end routes between source-destination pairs. Among these algorithms, FR is considered to be the simplest among all, whereas AR provides the best performance in terms of call blocking. FAR offers a trade-off between time complexity and call blocking. Briefly discussion on these algorithms are presented in the following subsections.

2.3.1 Fixed Routing (FR)

In fixed routing, a single fixed end-to-end route is precomputed for each source-destination pair using some shortest path algorithms, such as Dijkstras algorithm [44]. When a connection request arrives in the network, this algorithm attempts to establish a lightpath along the predetermined fixed route. It checks whether a required wavelength is available on each link of the predetermine end-to-end route or not. If no wavelength is found available, the connection request is blocked. In the situation when more than one required wavelength is available, a wavelength selection mechanism is used to select the best wavelength.

2.3.2 Fixed Alternate Routing (FAR)

Fixed alternate routing is an updated version of the FR algorithm. In FAR, each node in the network maintains a routing table (that contains an ordered list of a number of fixed end-to-end routes) for all other nodes. These routes are computed off-line. When a connection request with a given source-destination pair arrives, the source node attempts to establish a lightpath through each of the route from the routing table taken in sequence, until an end-to-end route with a required wavelength is found. If no available route with required wavelength is found from the list of alternate routes, the connection request is blocked. In the situation when more than one required wavelength is available on the selected end-to-end route, a wavelength assignment mechanism is applied to choose the best wavelength. Although the computational complexity of this algorithm is higher than that of FR, it provides comparatively lesser call blocking than the FR algorithm. However, this algorithm may not be able to find all the possible routes between a given source-destination pair. Therefore, the performance of FAR algorithm in terms of call blocking is not the optimum.

2.3.3 Least Congested Routing (LCR)

Least congested routing predetermines a sequence of end-to-end routes is for each source-destination pair similar to FAR. Depending on the arrival time of connection requests, the least-congested routes are selected among the predetermined routes. The congestion on a link is measured by the number of wavelengths available on the link. If a link has fewer available wavelengths, it is considered to be more congested. The disadvantage of LCR is its higher computational complexity, and its call blocking is almost same as in FAR.

2.3.4 Adaptive Routing (AR)

In adaptive routing, end-to-end routes between source-destination pairs are chosen dynamically, depending on link-state information of the network. The network link-state information is determined by the set of all connections that are currently in progress. The most acceptable form of adaptive routing is adaptive shortest-cost-path routing, which is well suited for use in wavelength-routed optical networks. Under this approach, each unused link in the network has a cost of 1 unit, whereas the cost of each used link in the network is considered α. When a connection arrives, the shortest-cost path between source-destination pair is determined. If there are multiple paths with the same distance, one of them is chosen at random. In shortest-cost adaptive routing, a connection is considered blocked mainly when there is no route with required wavelength between source-destination pair. Since adaptive routing considers all the possible routes between source-destination pair, it provides lower call blocking, but its setup time is comparatively higher than other routing algorithms. AR requires extensive support from the control and management protocols to continuously update the routing tables at the nodes. Moreover, AR is more preferable for centralized implementation and less accepted to the distributed environment.

The functionality of the above mentioned routing algorithms are explained with the help of a sample example network as shown in Figure 2-1. It consists of 14 nodes (representing cities) and 21 bi-directional optical links. The fixed shortest route or primary route, alternate route, and adaptive route from source city CA to destination city L are shown in solid-red, dotted-green, and dashed-blue lines, respectively. Furthermore, the congested links are denoted as α. If a connection request for a connection from source city CA to destination city L arrives, only AR can be able to find an end-to-end route between CA and L.

Significant amount of works addressing different issues of routing have been reported in the literature. Table 2.1 summaries the major routing algorithms, comparing their performance in terms of blocking probability (BP), average setup time (AST) and time complexity (TC).

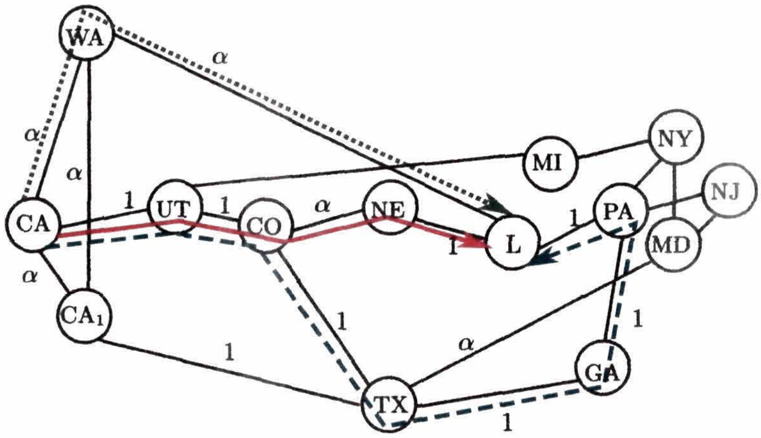


Figure 2-1: Fixed/primary (solid-red line), alternate (dotted-green line) and adaptive (dashed-blue line) routes are shown between source city CA to destination city L

Table 2.1: Summaries of different routing algorithms

Problem	Approach		Ref	Performance Analysis			On/Off line
				BP	AST	TC	
Routing + First-fit	Static	FR	[38]	More BP than others	Less AST than others	O (L_1 W Z)	Off line
		FAR	[39]	Less BP than FR	More AST than FR	O (L_2 K W Z)	Off line
		LCR	[43]	Almost same as FAR	Almost same as FAR	O (L_3 K W Z)	Off line
	Dynamic	AR	[40]	Less BP than others	More AST than others	O (L_2 N^2 W Z)	On line

L_1, L_2, L_3, W, K, N and Z are the length of the longest fixed route for any node pair, the length of the longest candidate route for any node pair, hop count of the longest candidate route, number of wavelengths per fiber link, the maximum number of candidate routes for any node pair, the number of nodes in the network and total number of connection requests in the network, respectively.

2.4 Wavelength Assignment

Wavelength assignment algorithm is used to select a suitable wavelength between a given source and destination pair when multiple feasible wavelengths are available on the end-to-end route of a connection request. Wavelength selection may be performed either after finding of a route for a lightpath or in parallel during the route selection process. In without wavelength conversion networks, the required wavelength for a lightpath is chosen in a manner which attempts to reduce call blocking for subsequent connection requests, while ensuring that no two lightpaths share the same wavelength on the same fiber link. Since wavelength assignment problem can be formulated as a graph coloring problem, it is an NP-Complete problem and therefore a number of heuristic solutions have been proposed in the literature [8,10,24,45–52]. Among these heuristics, some significant heuristics, such as first-fit, least-used, most-used, and random wavelength assignment schemes are briefly discussed in the following subsections.

2.4.1 First-fit (FF)

In first-fit scheme [8,10,24,45,46], the wavelengths are indexed and a list of indexes of available and used wavelengths is maintained. This scheme always attempts to choose the lowest indexed wavelength from the list of available wavelengths and assigns it to the lightpath to serve the connection request. When the call is completed, the wavelength is returned back to the list of available wavelengths. By selecting wavelengths in this manner, existing connections will be packed into a smaller number of wavelengths, leaving a larger number of wavelengths available for future use. To implement this scheme, no global information of the network is required. FF wavelength assignment scheme is considered to be one of the best scheme due to its lower call blocking and computational complexity.

2.4.2 Least-used (LU)

Least-used scheme [8, 10, 24] assigns a wavelength to a lightpath from the list of available wavelengths which has been used in the minimum number of fiber links throughout the network. If several available wavelengths share the same minimum usages, FF scheme is used to select the best wavelength among all the feasible wavelengths. By selecting wavelengths in this manner, it attempts to spread the load evenly across all wavelengths.

2.4.3 Most-used (MU)

Most-used scheme [8, 10, 24] has been used to assign a wavelength to a lightpath from the list of available wavelengths, which has been used in the maximum number of fiber links throughout the network. Similar to LU, if several available wavelengths share the same maximum usage, FF scheme is used to break the tie.

By selecting wavelengths in this way, it attempts to provide maximum wavelength reuse in the network.

2.4.4 Random Wavelength Assignment (R)

In random scheme [10, 24, 45], a list of free or available wavelengths is maintained. When a connection request arrives in the network, this scheme randomly selects a wavelength from the list of available wavelengths and assigns it to the lightpath used to serve the connection request. After assigning a wavelength to a lightpath, the list of available wavelengths is updated by deleting the used wavelength from the free list. When call is completed, the wavelength is again added to the list of free or available wavelengths. By selecting a wavelength at random manner, it can reduce the possibility of choosing the same wavelength by multiple connections in the situation when wavelength assignment is done in a distributed manner.

To illustrate the functionality of the above mentioned wavelength assignment schemes, we use an example network segment as shown in Figure 2-2. Both the wavelengths λ_1 and λ_2 are available from node-13 to node-10. If a connection request arrives at node-13 for establishing a lightpath to node-10, following strategy may be adopted. FF scheme selects the wavelength λ_1. Wavelengths λ_1 and λ_2 have been used eight times and four times, respectively, in the network segment. Therefore, λ_1 and λ_2 can be used for LU and MU wavelength assignment schemes, respectively. Random scheme selects any of the two wavelengths with an equal probability.

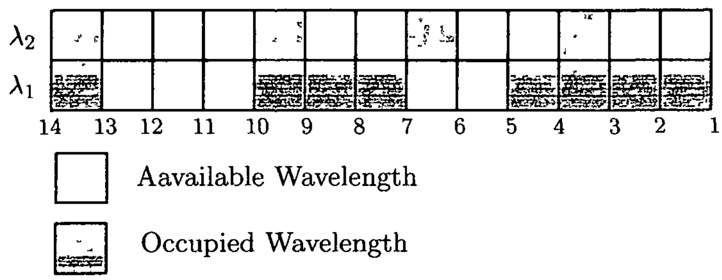


Figure 2-2: Wavelength-usage pattern for a network segment

Significant amount of works addressing different issues of wavelength assignment problem have been reported in the literature. Table 2.2 summarizes some major wavelength assignment schemes comparing their performance in terms of two major parameters, namely, blocking probability (BP) and time complexity (TC).

Table 2.2: Summaries of different wavelength assignment mechanisms

Problem	Approach	References	Performance analysis		Applicable Network
			BP	TC	
Wavelength Assignment + Fixed Routing	Max Sum (MS)	[24]	In multi-fiber, MS outperforms when load is high	O (L_1 W N^3 Z)	Single/multi-fiber networks
	Relative Capacity Loss (RCL)	[24]	In single fiber, RCL performs well when load is high	O (L_1 W N^3 Z)	Single/multi-fiber networks
	Min-product (MP)	[24]	MP performs well under low load	O (L_1 M N W Z)	Normally used in multi-fiber networks
	Least-loaded (LL)	[24]	LL performs well under high load	O (L_1 M N W Z)	Normally used in multi-fiber networks
	Least-used (LU)	[8, 10, 24]	LU perform well under high load	O (L_1 E W Z)	Single/multi-fiber networks
	Most-used (MU)	[8, 10, 24]	MU perform well under low load	O (L_1 E W Z)	Single/multi-fiber networks
	Random (R)	[10, 24, 45]	More BP than FF but almost close	O (L_1 W Z)	single/multi-fiber networks
	First-fit (FF)	[24, 45, 46]	Less BP among LU, MU, R	O (L_1 W Z)	single/multi-fiber networks

L_1, E, M, N, W and Z are the length of the longest fixed route for any node pair, total number of links in the network, total number of fibers in the network, total numbers of nodes in the network, number of wavelengths per fiber link, and total number of connection requests respectively

From the literature, it has been revealed that the majority of connection requests are in the Mbps range and a single wavelength channel in a WDM based system can support an enormous bandwidth of the order of 100 Gbps which is commercially available [53]. This has opened up a new opportunity in the form of traffic grooming which is discussed in the next section.

2.5 Traffic Grooming

In WDM based wavelength-routed optical networks, traffic grooming [10, 54–56, 56–61] has been used to multiplex a number of low-speed connection requests onto a high-capacity wavelength channel for enhancing channel utilization. Different kinds of multiplexing mechanisms [60] have been applied for traffic grooming in the different domains of optical networks, such as (i) Space Division Multiplexing (SDM), (ii) Frequency Division Multiplexing (FDM), (iii) Time Division Multiplexing (TDM) and (iv) Packet Division Multiplexing (PDM). However, most of the research in traffic grooming mainly focus on TDM approach.

Angela L. Chiu *et al.* [55] have proved that the traffic grooming problem in WDM based optical network is NP-complete [44]. They have shown that the Bin Packing problem can be transformed into the traffic grooming problem within a polynomial time. However, ILP formulation can be used to obtain an optimal solution for a smaller size network. In this direction, J. Wang *et al.* [57,61] have formulated traffic grooming problem as ILP. The limitation of the ILP approach is that the numbers of variables and equations increase exponentially with increase in network's size. By relaxing some constraints in ILP formulation, it may be possible to obtain optimal result for reasonable-size networks. The results of ILP may provide the insight and intuition for developing efficient heuristic algorithms for handling traffic grooming in a large network. In this direction, Keyao Zhu and Biswanath Mukherjee [10,60] have proposed two heuristics on traffic grooming, namely, (i) Maximizing Single-hop Traffic (MST) and (ii) Maximizing Resource Utilization (MRU) to increase the network throughput for large networks. Depending on the number of lightpaths allowed in a connection route, traffic grooming mechanisms have been mainly classified into two categories, namely, (i) single-hop grooming and (ii) multi-hop grooming. These approaches are briefly discussed in the following subsections.

2.5.1 Single-hop Traffic Grooming

Single-hop traffic grooming aggregates calls on a single lightpath to eliminate intermediate electronic processing. In single-hop traffic grooming, low-data-rate client traffic can be multiplexed onto wavelengths and all traffic that is carried over a given wavelength channel is switched to the same destination port. This type of traffic grooming does not have the capabilities of switching traffic at intermediate nodes. The grooming unit in this case is a traffic aggregation unit. The single-hop traffic grooming scheme has limited grooming capability since it can groom only traffic from the same source node to the same destination node. Therefore, this end-to-end grooming scheme restricts a connection to use only a single lightpath. As a result, the bandwidth of a lightpath cannot be shared by traffic from different source-destination pairs. Although the computation complexity and traffic delay in the network using single-hop traffic grooming is lower than that of using multi-hop traffic grooming, the performance of single-hop traffic grooming in terms of channel utilization is not the optimum. Figure 2-3 shows how a connection, denoted as C_1, is being carried by a lightpath, say L_1, from node-1 to node-9 using the single-hop traffic grooming scheme.

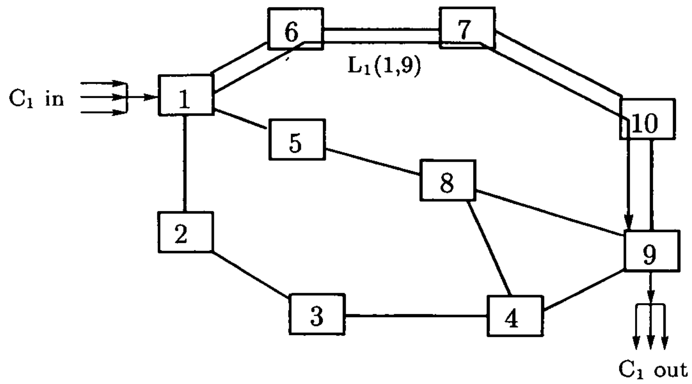


Figure 2-3: Example of single-hop traffic grooming

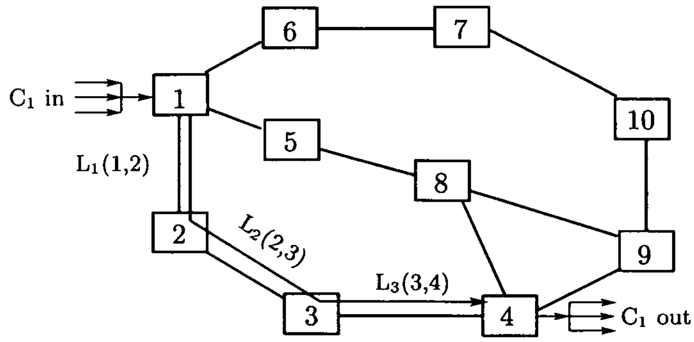


Figure 2-4: Example of multi-hop traffic grooming

2.5.2 Multi-hop Traffic Grooming

Multi-hop traffic grooming can aggregate calls on several lightpaths to enhance the channel utilization. Here, connections from different source-destination pairs share the bandwidth of a lightpath. Depending on the architectures of different grooming optical cross-connects (OXCs), multi-hop traffic grooming can be categorized into two types, namely, (i) multi-hop partial-grooming and (ii) multi-hop full-grooming. The details description about different types of grooming OXCs with their corresponding grooming schemes can be found in [10, 60]. The multi-hop full-grooming OXC can provide best performance in terms of resource utilization and blocking characteristics, but it can only be implemented using the opaque technology. Therefore, it requires a significant amount of electronic processing, which produces traffic delay in the network and increases the network setup cost. The multi-hop partial grooming approach offers reasonable alternative when full grooming is not necessary in each and every node. Figure 2-4 shows how a connection, denoted as C_1, can be carried by multiple lightpaths, such as L_1, L_2, and L_3 from node-1 to node-4.

Significant amount of works have been reported in the literature to address the different issues of traffic grooming. Table 2.3 summarizes the major traffic grooming mechanisms from literature.

Table 2.3: Summaries of different traffic grooming mechanisms

Problem	Traffic	References	Network architecture	Outcomes
Wavelength Assignment + Fixed Routing	Dynamic and static	[62, 63]	Single-hop and multi-hop optical ring	(i) Minimizing transceiver cost (ii) Study of dynamic traffic
	Egress and static	[55]	Unidirectional ring with egress node (single-hop) and bi-directional ring (single-hop)	(i) Proof of NP-completeness (ii) Optimal solution for uniform traffic on egress ring
	Static	[64, 65]	Bi-directional ring with odd number of nodes (single-hop)	(i) How to group timeslots (ii) Maximal and super node model for distance dependent traffic
	Static	[66]	Unidirectional and bi-directional ring (single-hop)	(i) Greedy heuristic for grooming arbitrary traffic (ii) Heuristic for circle construction for non-uniform traffic.
	Static	[10, 57]	Unidirectional and bidirectional ring (single-hop)	(i) Simulated-annealing-based heuristic for traffic grooming (ii) Greedy heuristic for single-hop and multi-hop grooming
	Poisson	[67–69]	Multi-hop mesh network	(i) Maximize channel utilization (ii) Maximize network throughput
	Poisson	[8, 10]	Single-hop mesh network	(i) Maximize channel utilization

It has been revealed from the literature survey that traffic grooming mechanism has emerged as an emerging technology which has been incorporated with the RWA approach to further enhance the utilization of optical channel capacity [67]. As a result, nowadays a single fiber can carry a huge amount of information which is of the order of Tbps range. A relatively important issue is survivability or fault management which plays a crucial role in WDM based optical networks. We discuss about fault management in WDM based optical networks in the next section.

2.6 Fault Management

Nowadays, WDM based optical networks are designed in such way that they have the capabilities to quickly detect, isolate and recover from a failure. Failure recovery [70] in an optical network is defined as "*the process of re-establishing traffic continuity in the event of a failure condition affecting that traffic, by re-routing the signals on diverse facilities after the failure*". A network is defined as survivable [70], if the network is capable to recover failure in the event of a fault occurrence. Many studies [10, 71–74] have been carried out for fault management in WDM based optical networks. In this direction, D. Zhou *et al.* [71] and S. Sengupta *et al.* [75] have summarized the solutions of recovery mechanisms for ring and mesh based optical networks. WDM based optical networks incorporate two types of fault recovery techniques [10,70,74], namely, (i) protection based and (ii) restoration based, which are discussed in the following subsections.

2.6.1 Protection

In protection, backup paths carry signals after the fault occurrence and they are computed prior to fault occurrence, but they are reconfigured after the fault occurrence. Ramamurthy *et al.* [76] have investigated different protection techniques from an implementation perspective. It has been observed from their study that most of the earlier research have concentrated on single node/link failure at a given instant. However, recent research has started to address the dual failure problems in optical networks. In this direction, Hongsik Choi *et al.* [77], M Clouqueur *et al.* [78], Ning-Hai Bao *et al.* [79] and Victor Yu Liu *et al.* [80] have addressed the dual failure problem in optical networks. Protection techniques have been classified based on resource sharing into two categories - (i) dedicated protection and (ii) shared protection, which are discussed as follows.

2.6.1.1 Dedicated Protection

In dedicated protection [10,70], a dedicated path is reserved for each working path, an example of this is shown in Figure 2-5. It has been observed from the literature survey that two types of dedicated protection [10, 70], namely, (i) 1+1 protection and (ii) 1:1 protection have been mainly considered for recovery purpose.

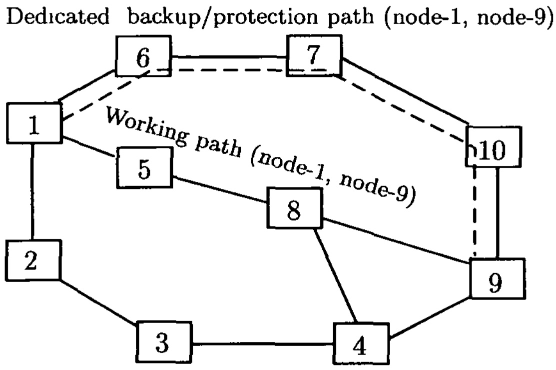


Figure 2-5: Example of dedicated backup/protection path from node-1 to node-9

- **1+1 Protection**: In 1+1 protection technique, from the source node optical signal is transmitted both on the working path as well as on the backup path. If the working path fails, the signal is switched over to the backup path and thus continues with data transmission. To avoid ambiguity, before sending signal on the backup path, the source node waits for some amount of time (denoted as t_1) after sending signal on the working path. The waiting time, t_1, may be computed depending on either the difference in propagation delay between the working path and the backup path or the failure-detection time. If the k^{th} bit of data reaches the destination at time, say t_2, through the working path, the same k^{th} bit should reach the destination at time, say t (where, $t \geq t_1+t_2$) through the backup path. If the destination node receives the $(k - 1)^{th}$ bit at that time, the fault controller detects a fault on the working path. Therefore, the signal is switched over to the backup path to retransmit the k^{th} bit.

- **1:1 Protection**: 1:1 protection technique does not allow transmission of signal on the backup path. However, the backup path is used to carry some low-priority preemptable traffic. If any fault occurs on the working path, the source node is notified by some protocol and then the signal is switched over to the backup path. Some data may be lost in the network, and the lost data can be recovered by retransmitting at the source node.

2.6.1.2 Shared Protection

Although dedicated protection can provide more reliability in the network, but it is unable to utilize the network resources properly. To overcome this problem, shared protection technique [10,70] has been applied in optical networks. In shared protection, a backup path is shared among all the working paths (1:M), but the working paths are not activated simultaneously. Therefore, the recovery time using shared protection is longer compared to dedicated protection. Figure 2-6

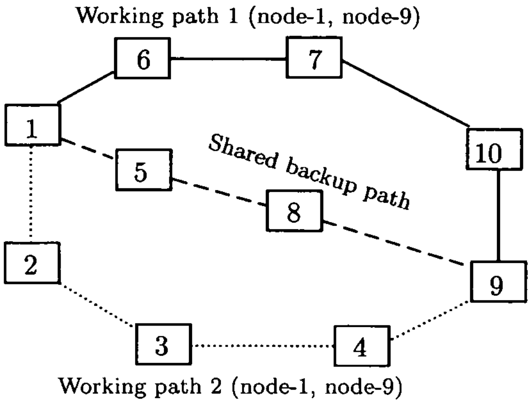


Figure 2-6: Example of shared backup/protection path from node-1 to node-9

shows an example of using shared protection. Two working paths, as for example 1-6-7-10-9 and 1-2-3-4-9 from node-1 to node-9 share a backup path 1-5-8-9, as the backup path is link and node disjoint to both the working paths.

2.6.2 Restoration

In restoration [10, 70, 74, 81, 82], backup paths are computed dynamically on the basis of link-state information after the fault occurrence, and hence it can provide more efficiency in terms of resource utilization compared to protection. As restoration technique can find the backup paths after the fault occurrence, therefore the recovery time of restoration is slower compared to protection. Depending on the type of rerouting, restoration can be classified mainly three categories, namely, (i) link restoration, (ii) path restoration and (iii) segment-based restoration. Link restoration [74] discovers a backup path of the failed connection only around the failed link. In path restoration [74], the failed connection independently discovers a backup path on an end-to-end basis. Segment-based restoration [74] discovers a segment backup path of the failed connection. Among these restorations, link restoration is considered to be a fastest restoration technique. However, the recovery time of path restoration is the maximum.

2.7 Conclusion

In this chapter, we have presented a comprehensive survey on the existing works related to the problems addressed in this dissertation. With a detailed understanding of the state of the art, the research contributions are presented in the subsequent chapters.

Chapter 3

Performance Analysis of Major Conventional RWA Schemes

3.1 Introduction

Routing and wavelength assignment (RWA) [8, 10] is considered to be one of the key functionality for WDM based optical networks, due to its information transparency and wavelength reuse characteristics. RWA selects the best end-to-end route and assign the suitable wavelength to establish a lightpath for serving a connection request. If a lightpath for a connection request cannot be established within holding time[1], it is treated as a blocked connection. In a WDM based wavelength-routed optical network, RWA approaches can play the crucial role to improve the network performance. The performance of the network depends on the selection of RWA approach. In this context, this chapter provides the performance analysis of the major conventional RWA approaches in terms of call blocking. The rest of this chapter is organized as follows. Section 3.2 formally defines the problem and describes the constraints used for RWA approaches throughout this dissertation. In this section we also address the model assumptions, and define the basic terms, symbols and notations which are used throughout this chapter as well as this dissertation. The performance of major conventional RWA approaches is evaluated through simulation study in section 3.3. Further, in this section we also analyze about the pros and cons of major routing algorithms and wavelength assignment schemes based on the simulation results. Finally, section 3.4 concludes this chapter.

[1]which is supplied by the network designer according to user requirement and the connection request should be established within this time.

3.2 Problem Statement

We model the physical topology of an optical network as a connected graph G' (V', E'), where V' and E' are the set of nodes and set of bi-directional optical fiber links in the network, respectively. Here, each link $e \epsilon E'$ has a finite number of wavelengths denoted by W. A non-negative link cost $C(e)$ is assigned to every link e in the network, which represents the distance between the adjacent node pair connected by e. The following assumptions are considered in our model.

3.2.1 Assumptions

- Each fiber link can carry an equal number of wavelengths and the network is without wavelength conversion capabilities.
- All the lightpaths sharing at least one fiber link are allocated distinct wavelengths.
- Each node can work as both an access node and a routing node.
- Each node is equipped with a fixed number of tunable transceivers.
- All channels have the same bandwidth.

3.2.2 Definitions and Notations

The following definitions and notations [8] that have been used for RWA approaches throughout this chapter as well as this dissertation are explained below.

- **Distance matrix :** Distance matrix, denoted as D_{matrix}, specifies the distances between adjacent node pairs. It is a two-dimensional matrix with N rows and N columns. An entity in D_{matrix} corresponds to the distance from node x to node y and it is represented by $d^{x,y}$.
- **Traffic matrix :** Traffic matrix, denoted as T_{matrix}, specifies the average traffic flow between node pairs. It is a two-dimensional matrix with N rows and N columns. An entity in T_{matrix} corresponds to the average traffic flow from node x to node y which is denoted by $t^{x,y}$.
- **Hop matrix :** Hop matrix, denoted as H_{matrix}, specifies the allowable maximum number of physical hops in a lightpath between a node pair. It is

a two-dimensional matrix with N rows and N columns. An entity in T_{matrix} corresponds to the allowable number of physical hops in a lightpath from node i to node j and it is represented by $h^p_{i,j}$.

- **Link indicator:** It indicates the existence of physical links between node pairs. The value of this indicator variable, denoted as $l^{x,y}$, is 1, if there exists a physical link from node x to node y. Otherwise its value is 0.

- **Lightpath indicator** : It indicates the existence of a lightpaths between node pairs The value of this indicator variable, say $P_{i,j}$, is 1, if there exists a lightpath from node i to node j. Otherwise its value is 0.

- **Lightpath-wavelength indicator** : It indicates the existence of lightpaths with particular wavelengths between node pairs. The value of this indicator variable, denoted by $P_{i,j,\lambda}$, is 1, if there exists a lightpath from node i to node j and it is assigned to wavelength λ. Otherwise its value is 0.

- **Lightpath-wavelength-link indicator** : This indicator is used to indicate the existence of lightpaths on specific wavelengths between node pairs and it uses particular physical links. The value of this indicator variable, say $P^{x,y}_{i,j,\lambda}$, is 1, if there exists a lightpath from node i to node j and it uses wavelength λ on a physical link from node x to node y. Otherwise its value is 0.

- **Virtual hop distance** : Virtual hop distance, denoted as $h_{i,j}$, from node i to node j is the number of virtual hop from node i to node j on the virtual topology.

- **Traffic flow and bandwidth** : The component of traffic due to a source-destination node pair offered onto a lightpath from node i to node j which is denoted by $\alpha^{s,d}_{i,j}$. C_B and $B^{s,d}$ are the maximum bandwidth of a channel and a connection between source-destination node pair, respectively.

3.2.3 Constraints

The following constraints [8] which have been used for RWA approaches throughout this chapter as well as this dissertation are explained below.

- **Virtual degree constraints** : Virtual degree constraints that relate the number of transmitters and receivers for each node in the network are given below.

$$\sum P_{j,i} \leq D^v_{in} \quad \forall i \tag{3.1}$$

$$\sum P_{i,j} \leq D^{v}_{out} \quad \forall j \tag{3.2}$$

Equations (3.1) and (3.2) state that the virtual out-degree (D^{v}_{out}) and in-degree (D^{v}_{in}) of each node is same in the network.

- **Wavelength constraints** : Wavelength constraints that pertain to the assignment of wavelengths to lightpaths for serving connection requests in the network are given below.

$$P_{i,j} = \sum_{\lambda=0}^{W-1} P_{i,j,\lambda} \quad \forall (i,j) \tag{3.3}$$

$$P^{x,y}_{i,j,\lambda} \leq P_{i,j,\lambda} \quad \forall (i,j),(x,y),\lambda \tag{3.4}$$

$$\sum P^{x,y}_{i,j,\lambda} \leq 1 \quad \forall (x,y),\lambda \tag{3.5}$$

Equations (3.3), (3.4) and (3.5) state the wavelength used by a lightpath is unique, wavelength continuity constraint and distinct channel constraint, respectively.

- **Bandwidth constraint** : Bandwidth constraint relates the bandwidth of a connection and the maximum capacity of a channel in the network which is given below.

$$B^{s,d} \leq C_B \tag{3.6}$$

Equation (3.6) states that the bandwidth of a connection between a source-destination node pair does not exceed the channel capacity.

- **Hop constraint** : Hop constraint that pertains to the number of physical links traversed by a lightpath in the network is given below.

$$\sum P^{x,y}_{i,j,\lambda} \leq h^{p}_{i,j} \quad \forall (i,j),\lambda \tag{3.7}$$

Equation (3.7) states that the number of physical links traversed by a lightpath is at most a value specified by the physical hop matrix, H_{matrix}.

- **Variable value constraints** : The constraint given by Equation (3.8) ensures that the traffic flow on a lightpath due to a node pair is a positive quantity.

$$\alpha^{s,d}_{i,j} \geq 0 \quad \forall (i,j),(s,d) \tag{3.8}$$

Lightpath indicator, link indicator, lightpath-wavelength indicator, lightpath-wavelength-link indicator are binary variables and they are captured by the following constraints.

$$P_{i,j} \in 0,1 \quad \forall(i,j) \tag{3.9}$$

$$l_{x,y} \in 0,1 \quad \forall(x,y) \tag{3.10}$$

$$P_{i,j,\lambda} \in 0,1 \quad \forall(i,j),\lambda \tag{3.11}$$

$$P^{x,y}_{i,j,\lambda} \in 0,1 \quad \forall(i,j),(x,y),\lambda \tag{3.12}$$

3.3 Performance Analysis

In this section we will present simulation results in two experimental setups to evaluate the performance of some major conventional RWA approaches in terms of call blocking. Our experimental setup consists of 14 nodes with 24 bi-directional physical links of the Indian network and 14 nodes with 21 bi-directional physical links of NSFNET [10] as shown in Figure 3-1 and Figure 3-2, respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are taken as given in Figure 3-1 and Figure 3-2 for configuring the example networks - the Indian network and NSFNET, respectively.
- The connection requests are generated randomly based on a Poisson process, and the arrival time between two successive requests follows an exponential distribution. We choose the Poisson model because the burstiness of traffic on the backbone is usually suppressed by the huge amount of aggregation of services and the actual traffic distribution remains unknown.
- The holding times of the connection requests are exponentially distributed. For the sake of simplicity, the holding time of all the connection requests having same source-destination pair are assumed to be same. However, differences in holding times for connection requests having same source-destination pair can be handled by taking the maximum of their holding times (similar to [52]) as the holding time for all of them.
- For least-used wavelength assignment, we have blocked (considered as used wavelengths) few wavelengths (1%) randomly in the different links of the networks.

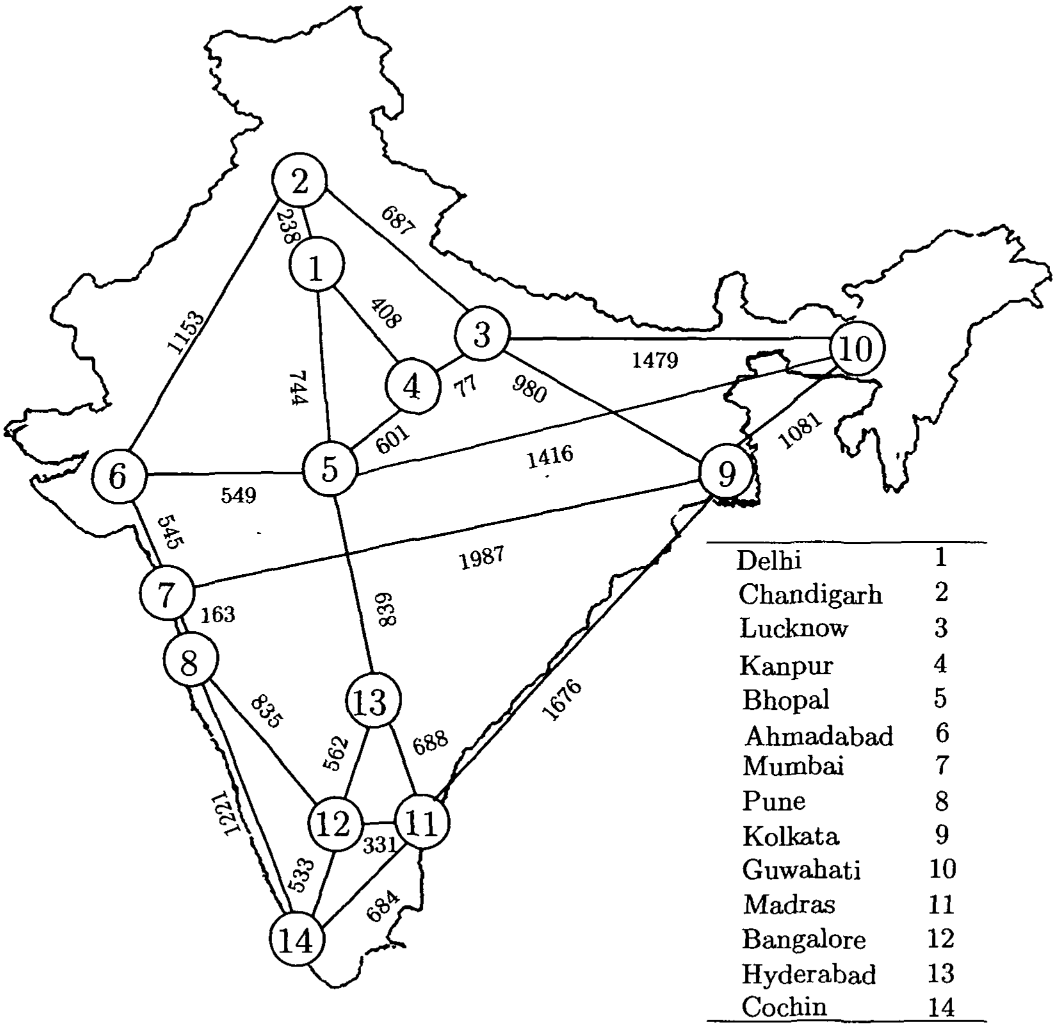
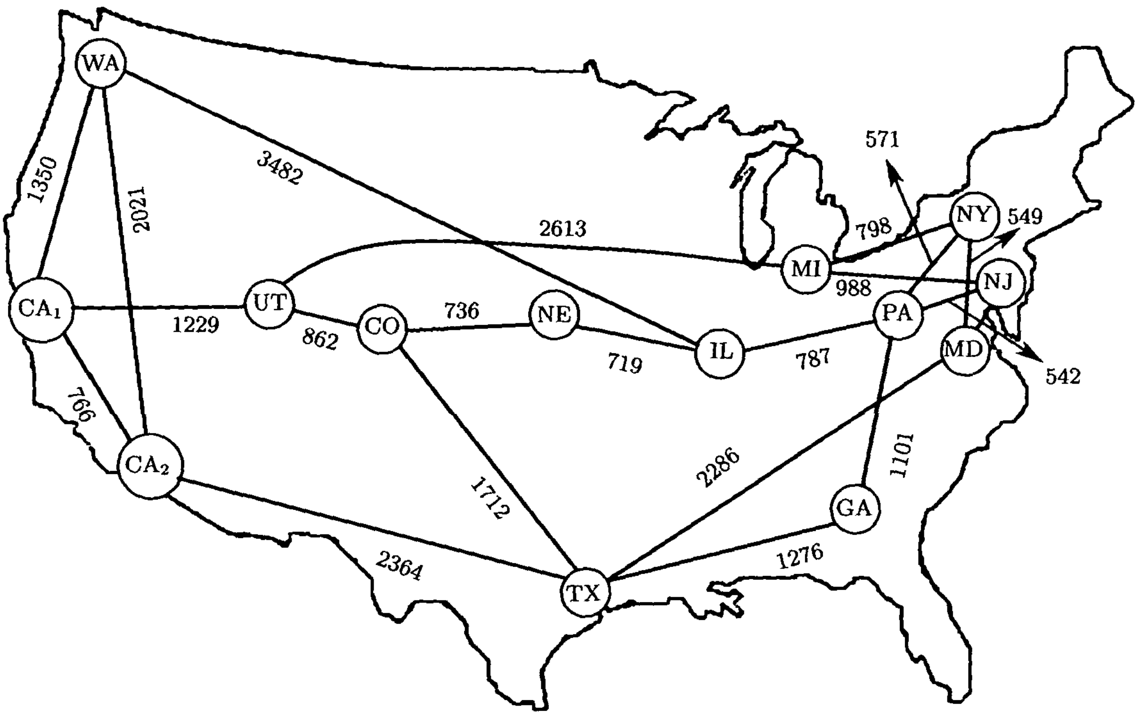


Figure 3-1: The Indian network and distances between its adjacent cities in kilometers.

- The maximum bandwidth requirement of a connection request is 622.08 Mbps according to SONET OC-12/STS-12 [9].
- The maximum capacity of each wavelength channel is 9953.28 Mbps according to SONET OC-192/STS-192 [9].

We have performed the simulation study of the routing algorithms and conventional wavelength assignment approaches. For this purpose, we generated a number of connection requests, distributed randomly among all the possible source-destination pairs.



WA	Seattle	PA	Pittsburgh
CA_1	Palo Alto	GA	Atlanta
CA_2	San Diego	MI	Ann Arbor
UT	Salt Lake City	NY	Ithaca
TX	Houston	NJ	Princeton
CO	Boulder	MD	College Park
NE	Lincoln	IL	Champaign

Figure 3-2: National Science Foundation Network (NSFNET) and distances between its adjacent cities in kilometers.

3.3.1 Routing

Here, we will show the performance of routing algorithms in terms of blocking probability and average setup time which are defined in Equation (3.13) and Equation (3.14), respectively. For wavelength assignment purpose, we take First-fit (FF) method, due to its lower call blocking and computational complexity compared to other wavelength assignment schemes.

$$\textit{Blocking Probability} = \frac{\textit{Total Number of Blocked Calls}}{\textit{Total Number of Connection Requests in the Network}} \qquad (3.13)$$

Figure 3-3 and Figure 3-4 show the blocking probability versus number of wavelengths in the Indian network and NSFNET, respectively, with 5000 connection requests. In both the figures, $K = 1$ corresponds to a primary path and other values of K (*i.e.* K >1) represent using K-1 number of alternate paths. It

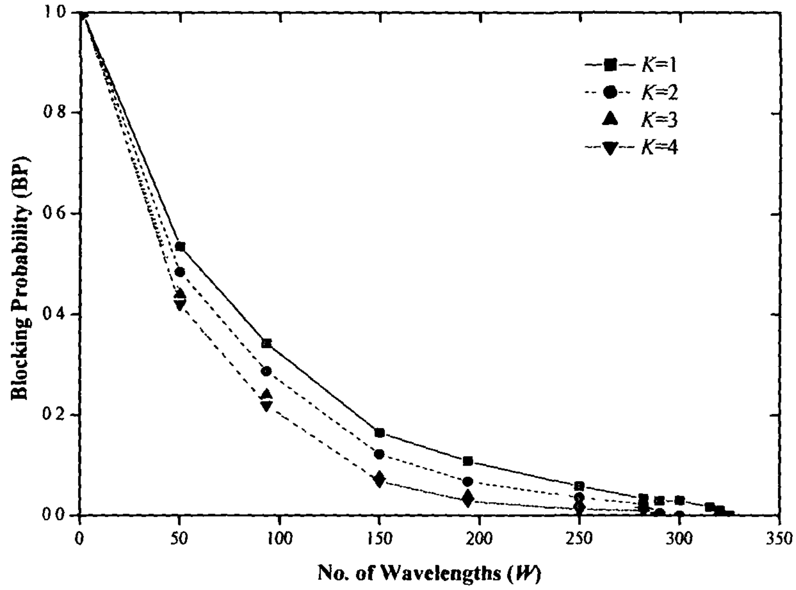


Figure 3-3: BP versus *W* for the different paths (*K* values) in the Indian network

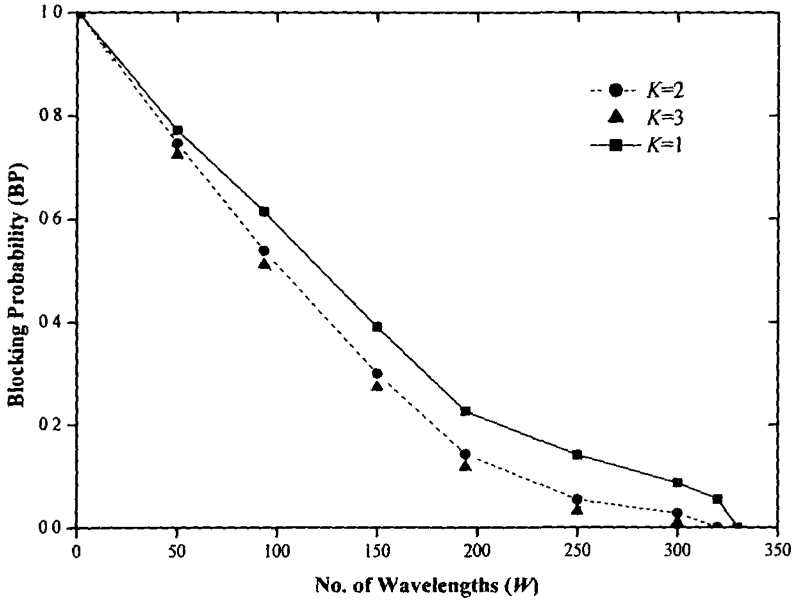


Figure 3-4: BP versus *W* for the different paths (*K* values) in NSFNET

has been revealed that in both the networks, blocking probability decreases with increase in number of wavelengths. On the other hand, blocking probability also decreases with the increase in number of paths. The variation of blocking probability with number of wavelengths, using up to three (*i.e.* K=4) alternate paths is close to that of using up to two (*i.e.* K=3) alternate paths in the Indian network. Similarly, in NSFNET, the variation of blocking probability using up to two (*i.e.*

K=3) alternate paths is close to that of using up to one (*i.e.* K=2) alternate path.

Figure 3-5 and Figure 3-6 show the average setup time versus number of wavelengths for the different paths in the Indian network and NSFNET, respectively, with 5000 connection requests. It has been observed from Figure 3-5 and Figure 3-6 that the average setup time [23] increases with increase in number of alternate paths. This is mainly due to extra time required to find the next alternate path. However, the average setup time of different paths remains almost constant after a particular number of wavelengths. This is because, all the connections in the network are established after a particular number of wavelengths.

$$Average\ Setup\ Time = \frac{Total\ Execution\ Time\ in\ the\ Network}{Total\ Number\ of\ Successful\ Connections} \tag{3.14}$$

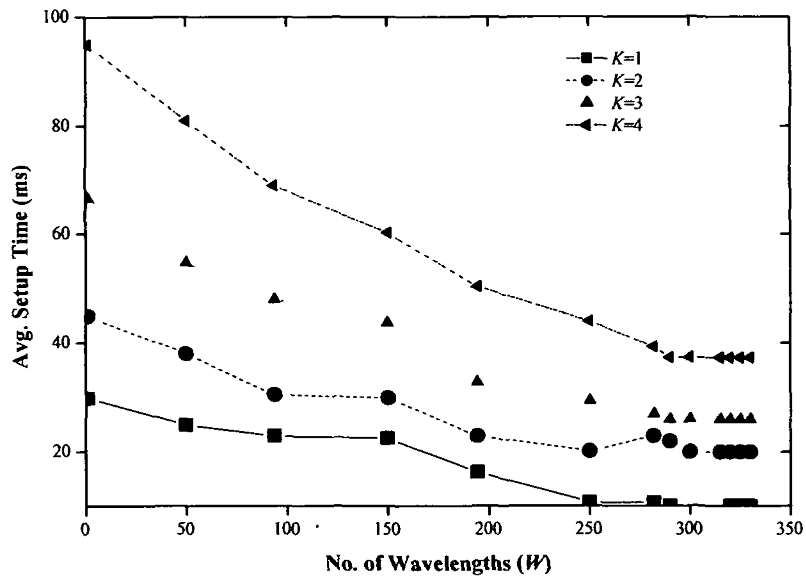


Figure 3-5: Average setup time versus W for the different paths in the Indian network

By analyses of Figure 3-3 to Figure 3-5, we can summarize that as the number of alternate paths increases, the blocking probability decreases and the average setup time increases. Therefore, it is required to trade off between blocking probability and average setup time. Thus, the number of alternate paths for RWA purpose is considered up to one and two for NSFNET and the Indian network, respectively. The same observation is being used for further analysis of routing and wavelength assignment approaches.

Figure 3-7 and Figure 3-8 show the blocking probability versus number of wavelengths for routing algorithms, namely, Fixed Routing (FR), Fixed Alternate Routing (FAR) and Adaptive Routing (AR) using FF method in the Indian

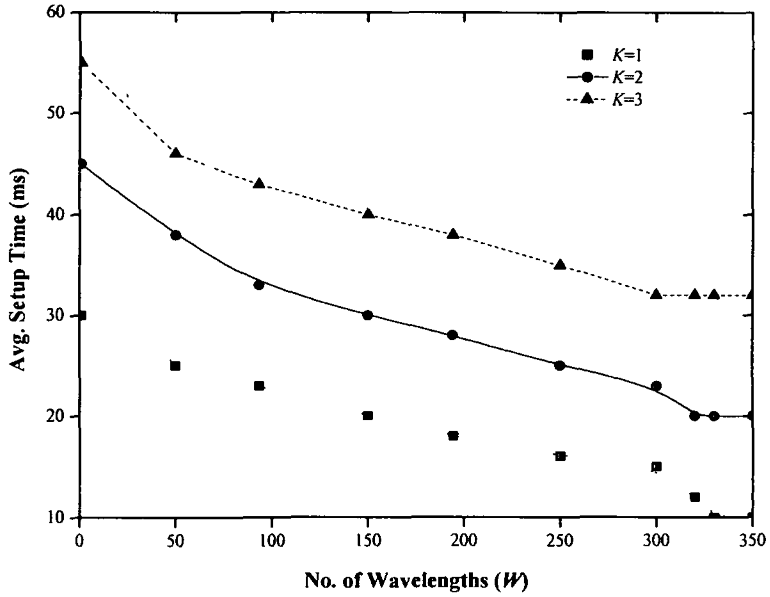


Figure 3-6: Average setup time versus *W* for the different paths in NSFNET

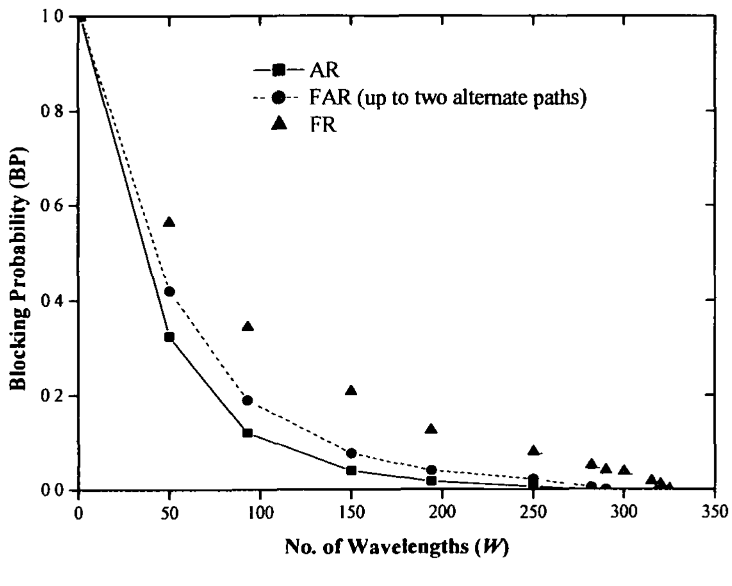


Figure 3-7: BP versus *W* for the different routing algorithms in the Indian network

network and NSFNET, respectively, with 5000 connection requests. From the literature study, it had been found that the performance of Least Congested Routing (LCR) in terms of call blocking is almost same as that of using FAR. Therefore, we do not consider LCR in our simulation study. It has been revealed from Figure 3-7 and Figure 3-8 that the blocking probability decreases with increase in number

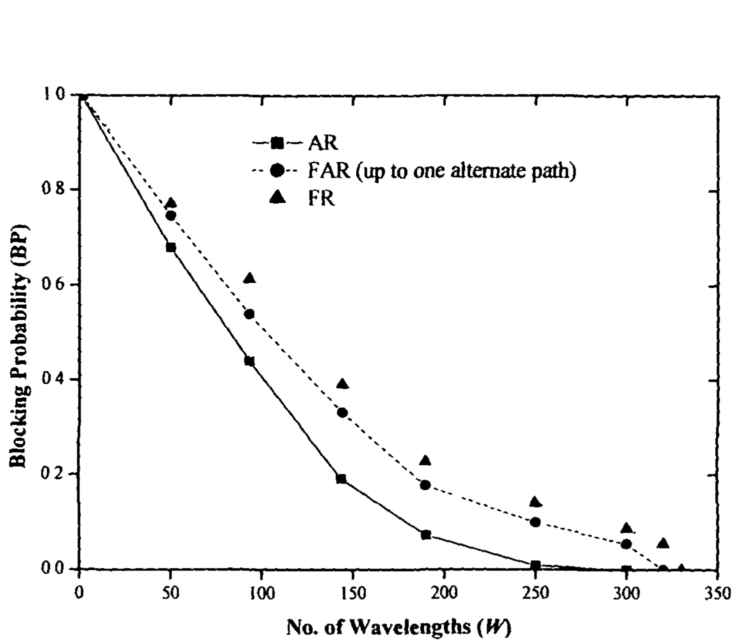


Figure 3-8: BP versus *W* for the different routing algorithms in NSFNET

of wavelengths irrespective of the routing algorithm used. However, the rate of decrease in blocking probability for AR is more than that of other routing algorithms. This is because, AR considers all the possible end-to-end routes between source-destination pair on the basis of link-state information. Furthermore, it can be observed that the blocking probability using FAR is less than that of using FR due to FAR's consideration of alternate paths for establishing connection requests. We also found that the blocking probability in the Indian network is less compared to NSFNET.

3.3.2 Wavelength Assignment

Here, we will show the performance of wavelength assignment schemes, namely, FF, Random (R) and Least-used (LU) in terms of blocking probability. From the literature, it had been revealed that the computational complexity of remaining conventional wavelength assignment schemes, such as Max-sum (MS), Relative Capacity Loss (RCL), Min-product (MP) and Least-loaded (LL) are much higher compared to FF, R and LU schemes. Therefore in our simulation study, we have only considered FF, Random and LU wavelength assignment schemes.

Figure 3-9 and Figure 3-10 show the blocking probability versus number of wavelengths using different wavelength assignment schemes in the Indian network and NSFNET, respectively, with 5000 connection requests. It has been revealed

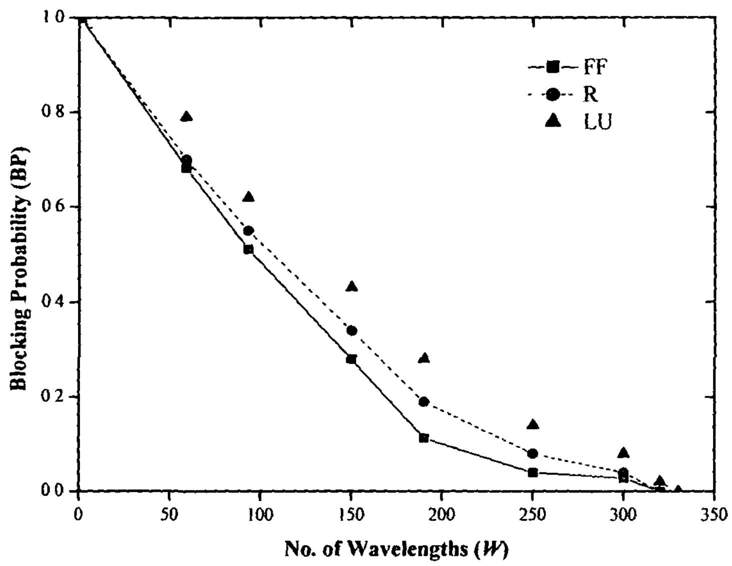


Figure 3-9: BP versus *W* for the different wavelength assignment schemes in the Indian network

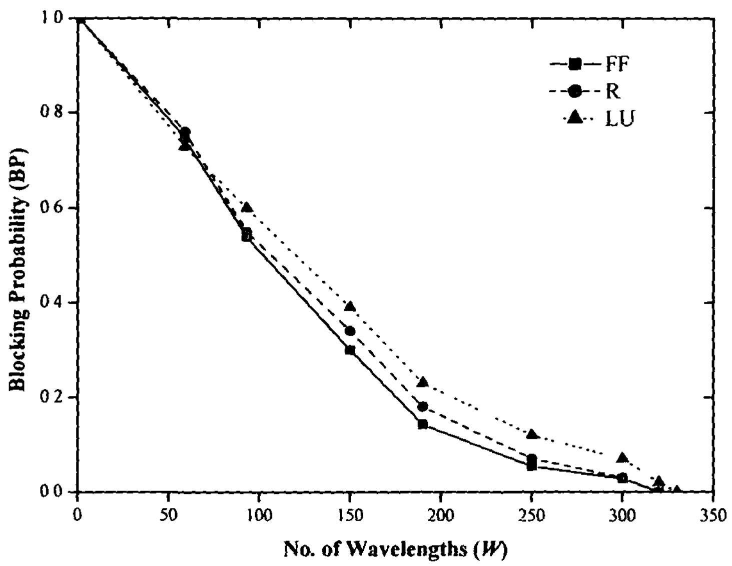


Figure 3-10: BP versus *W* for the different wavelength assignment schemes in NSFNET

from Figure 3-9 and Figure 3-10 that the blocking probability decreases with increase in number of wavelengths irrespective of the wavelength assignment scheme used. However, the rate of decrease in blocking probability using FF scheme is more than that of using other schemes. This is because FF always chooses the lowest indexed required wavelengths sequentially from the list of available wavelengths and attempts to spread the load evenly across all wavelengths. Furthermore, it can be observed from Figure 3-9 and Figure 3-10 that the blocking probability using random wavelength assignment scheme is close to that of using FF. On the other hand, the blocking probability using LU is more than that of using R and FF. This is because, some wavelengths might have been occupied by other lightpaths before applying the LU wavelength assignment scheme.

3.4 Conclusion

In this chapter, we have analyzed the performance of some major routing algorithms and conventional wavelength assignment approaches in the wavelength-routed optical networks. The effectiveness of the routing algorithms and wavelength assignment approaches have been examined through the performance evaluation in two example optical networks, namely, (i) the Indian network and (ii) NSFNET. From the simulation results we draw the following conclusions:

- It has been found that the performance of first-fit wavelength assignment approach in terms of blocking probability is the best among all the wavelength assignment schemes considered.
- Although adaptive routing with first-fit wavelength assignment scheme provides the best performance in terms of blocking probability, its average setup time is higher compared to others.
- Fixed alternate routing trades-off between blocking probability and average setup time.

Furthermore, it has been observed from the simulation study that for serving 5000 connection requests, a large number (~350) of wavelengths is required which is practically impossible (using C+L spectrum band) in a wavelength-routed optical network. To overcome this problem, traffic grooming mechanism can be incorporated with RWA approach, in which a number of low-speed connection requests are multiplexed onto a high-capacity wavelength channel to enhance overall channel utilization and minimize the call blocking in the network. In the next three chapters, we have incorporated traffic grooming mechanism with RWA approaches for better utilization of network's resources.

Chapter 4

Priority-based Routing and Wavelength Assignment Scheme

4.1 Introduction

One of the challenging issues in optical networks is reducing call blocking. Call blocking increases with number of connection requests due to availability of limited number of wavelength channels in fiber link. On the other hand, nowadays majority of connection requests are still in Mbps range. However, a single wavelength channel in a wavelength division multiplexing (WDM) based system has the potential to support an enormous communication-bandwidth in the order of 100 Gbps [1]. This has opened up a new opportunity in the form of traffic grooming [61, 69, 83–85]. It is possible to incorporate traffic grooming mechanism with RWA approach by multiplexing a number of low-speed connection requests onto a high capacity wavelength channel to enhance overall channel utilization in the network. Many conventional wavelength assignment approaches, such as, First-fit (FF), Random wavelength assignment (R), Least-used (LU), Most-used (MU), Min-product (MP), Least-loaded (LL), Max-sum (MS) and Relative Capacity Loss (RCL) have been reported in the literature [8, 10, 24, 38] for RWA purpose. Among these approaches, FF is considered to be one of the best in terms of call blocking, fairness and lower computational overhead. Although, wavelength reassignment algorithms using reconfiguration and minimum overlap techniques [86] have been proposed to reduce call blocking in the network, they able to reduce call blocking only moderately. This depletion does not fulfill the requirement of current network to exploit the large number of applications. Recently, prioritization concepts have been incorporated with RWA approach for reducing the call blocking in the network. However, the majorities of the prioritization approaches [87, 88] do not differentiate the connection requests and treat them the same way for RWA. Unfortunately, these approaches could not improve the performance of the network beyond a certain limit. In this direction, we explore the possibility of prioritizing connection requests to improve network performance. Accordingly, we differentiate connection requests into different priority groups based on types of path and volume of traffic for improving the performance. To the best of our knowledge, no priority-based routing and wavelength assignment scheme has been reported with incorporation of traffic grooming mechanism to reduce the call blocking, while maintaining the congestion level in the network.

In this chapter, we have proposed a priority-based routing and wavelength assignment (PRWA) scheme with incorporation of traffic grooming mechanism to reduce the call blocking, while maintaining the congestion level in the network. The results have been compared with a similar type of non priority-based routing and wavelength assignment (NPRWA) scheme. The rest of this chapter is organized as follows. Section 4.2 formally defines the problem and describes the constraints used for RWA approaches. There, we also address the model assumptions, and define symbols and notations which are used throughout this chapter. Section 4.3 presents the network node architecture, and describes the functionality of components of a network node. The PRWA scheme is presented in section 4.4. Further in that section, we elaborate the working principle of PRWA scheme with the help of some examples. Section 4.5 evaluates the performance of the PRWA scheme under blocking and non-blocking conditions. Finally, section 4.6 concludes this chapter.

4.2 Problem Statement

We model the physical topology of an optical network as a connected graph G' (V', E'), where V' and E' are the set of nodes and set of bi-directional optical fiber links in the network, respectively. Here, each link $e \epsilon E'$ has a finite number of wavelengths denoted by W. A non-negative link cost $C(e)$ is assigned to every link e in the network, which represents the distance between the adjacent node pair connected by e. The following assumptions are considered in our model.

4.2.1 Assumptions

- Each fiber link can carry an equal number of wavelengths and the network is without wavelength conversion capabilities.
- All the lightpaths sharing at least one fiber link are allocated distinct wavelengths.
- Each node can work as both an access node and a routing node.
- Each node is equipped with a fixed number of tunable transceivers.
- Each node is capable of multiplexing/demultiplexing as many connection requests having the same source-destination pair as possible within the channel capacity.
- All channels have the same bandwidth.

4.2.2 Notations and Symbols

For the remainder of this chapter, the symbols and notations used are summarized in Table 4.1.

Table 4.1: Used notations and symbols

Notations / Symbols	Comments
N	Total number of nodes in the network
E	Total number of links in the network
r	A connection request
s	The source of a connection request
d	The destination of a connection request
W	Total number of wavelengths per fiber link
L	Total number of physical links between a source-destination pair
Z	Total number of connection requests in the network
X	Total number of groomed connection requests in the network having direct physical link
U	Total number of groomed connection requests in the network having in-direct physical link
Y	Total number of groomed connection requests in the network ($Y = X + U$)

$\alpha_{i,j}^{s,d}$	Component of traffic offered onto a lightpath due to source-destination pair from node i to node j
$\alpha_{i,j}$	Total amount of traffic offered onto a lightpath from node i to node j
t_H	Holding time of a connection request. This time is supplied by the network designer according to user requirement. The connection request should be established within this time
K	Total number of lightpaths for a connection request
f_{max}	Maximum offered traffic flow on any lightpath or congestion in the network
$B(gr^{s,d})$	Bandwidth requirement of groomed connection request, $gr^{s,d}$ from source s to destination d
GR_1	Ordered set of groomed connection requests having direct physical link
GR_2	Ordered set of groomed connection requests having in-direct physical link
R	Set of all connection requests
$B(r_i^{s,d})$	Bandwidth requirement of a connection request
$gr_{D,i}^{s_i,d_i}$	The i^{th} groomed connection requests in GR_1
$gr_{I,i}^{s_i,d_i}$	The i^{th} groomed connection requests in GR_2
$Vol(gr_{I,i}^{s_i,d_i})$	Volume of traffic for the groomed connection request of $gr_{I,i}^{s_i,d_i}$
$Vol(gr_{D,i}^{s_i,d_i})$	Volume of traffic for the groomed connection request of $gr_{D,i}^{s_i,d_i}$

4.2.3 Constraints

The constraints [8] that have been used for RWA approach throughout this chapter are explained below.

- **Traffic flow constraints :** Traffic flow constraints relate the traffic routed over the lightpaths in the virtual topology.

$$\alpha_{i,j} = \sum_{s,d} \alpha_{i,j}^{s,d} \quad \forall(i,j) \tag{4.1}$$

$$\alpha_{i,j} \leq f_{max} \quad \forall(i,j) \tag{4.2}$$

Equation (4.1) states that the traffic offered onto a lightpath is the sum of the traffic offered onto the lightpath due to all the node pairs. The congestion of the network is expressed by using Equation (4.2).

- Virtual degree constraints, wavelength constraints, bandwidth constraint, hop constraint and variable value constraints are already explained in chapter 3 (page number 41). These constraints are also used in this chapter for RWA purpose.

4.3 Node Architecture

In a WDM based optical network, optical signals are transmitted through lightpaths. A connection request may traverse through one or more lightpaths before it reaches the destination. Two important functionality that must be supported by the nodes in an optical network are (i) wavelength routing and (ii) multiplexing / demultiplexing.

In order to control wavelength routing and multiplexing / demultiplexing in an optical network, a network node is being designed as per PRWA algorithm. The PRWA algorithm will be discussed later in section 4.4. Figure 4-1 shows the logical architecture of the network node which uses a number of devices, these are (i) F number of wavelength division multiplexers (WDMs) / wavelength division demultiplexers (WDDMs), (ii) W number of thermo-optic switches (TOSWs), (iii) W number of transmitters (TXs), (iv) W number of receivers (RXs), (v) W number of add-drop multiplexers (ADMs), (vi) a SONET STS multiplexer (SONET MUX)/ SONET STS demultiplexer (SONET DMUX) and (vii) a wavelength router based on PRWA algorithm. The functions performed by a network node are consists of three tasks that are explained briefly as follows:

(i) Initially, several connection requests arrive at the system randomly based on any distribution. The connection requests (as per bandwidth) having the same source-destination pair are groomed with SONET STS multiplexer. As an example, if connection requests of bandwidth 622.08 Mbps are groomed, a maximum 16 number of connection requests can be accommodated with SONET STS-192. These groomed connection requests are assigned wavelengths as per PRWA algorithm. The optical signals of the assigned wavelengths are sent by transmitters. Furthermore, transmitted

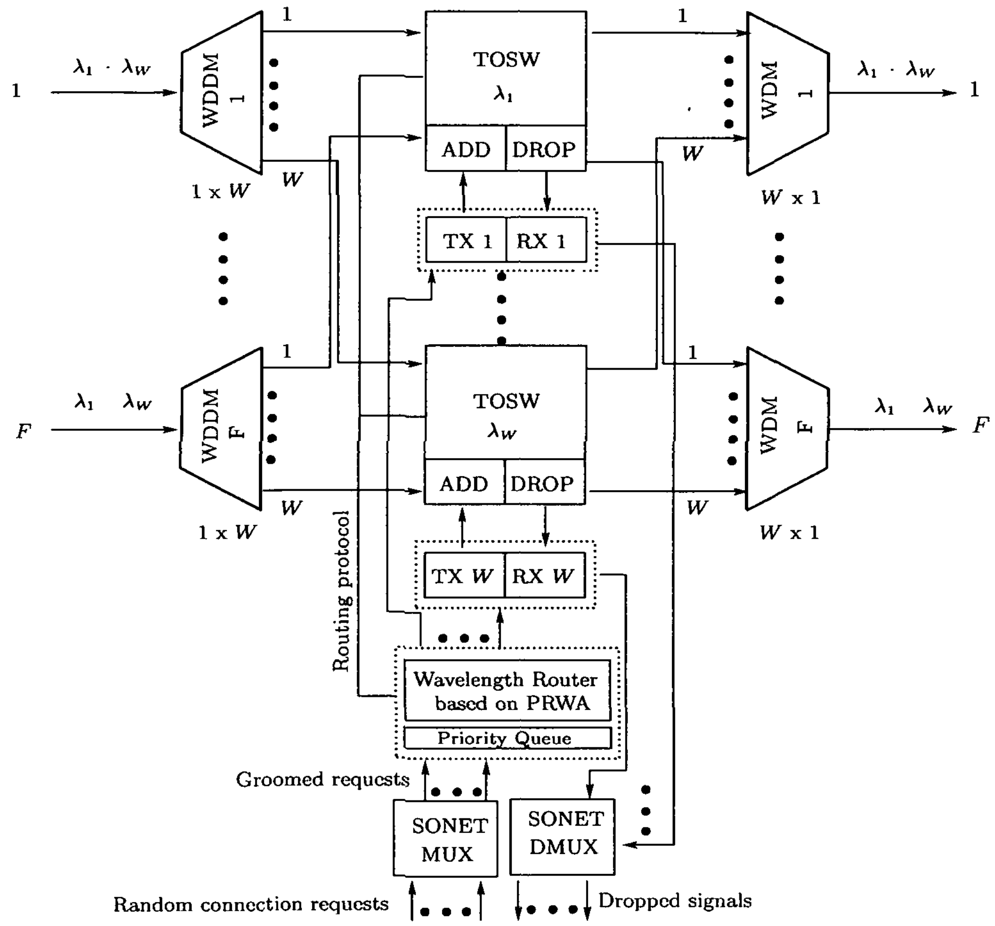


Figure 4-1: Network node architecture

signals are added to thermo-optic switches through the add-drop multiplexers. Then, the wavelengths are switched by thermo-optic switches. Finally, the wavelengths are multiplexed by wavelength division multiplexers at corresponding output fiber links in order to deliver the signals at destination nodes. This task is accomplished by wavelength router, with the application of PRWA algorithm.

(ii) On the other hand, the wavelengths from input fiber links are demultiplexed by wavelength division demultiplexers. The demultiplexed optical signals are switched by thermo-optic switches and finally multiplexed onto the corresponding output fiber link.

(iii) The wavelengths carrying the optical signals for the node itself are dropped through add-drop multiplexers. These dropped signals are demultiplexed by SONET STS demultiplexer in order to provide optical signals to end-users.

4.4 Priority-based Routing and Wavelength Assignment

A priority-based routing and wavelength Assignment (PWRA) scheme has been proposed to reduce the call blocking, while maintaining the congestion level in the network. In PRWA, there are mainly two steps involved in constructing the complete framework, namely, (i) grooming of connection requests and priority order estimation and (ii) routing and wavelength assignment (RWA). Connection requests grooming and priority order estimation is the first step to groom the connection requests and to estimate their priority order. Finally, groomed connection requests are served for wavelength assignment according to their priority order. The overall framework of this scheme is being depicted in Figure 4-2.

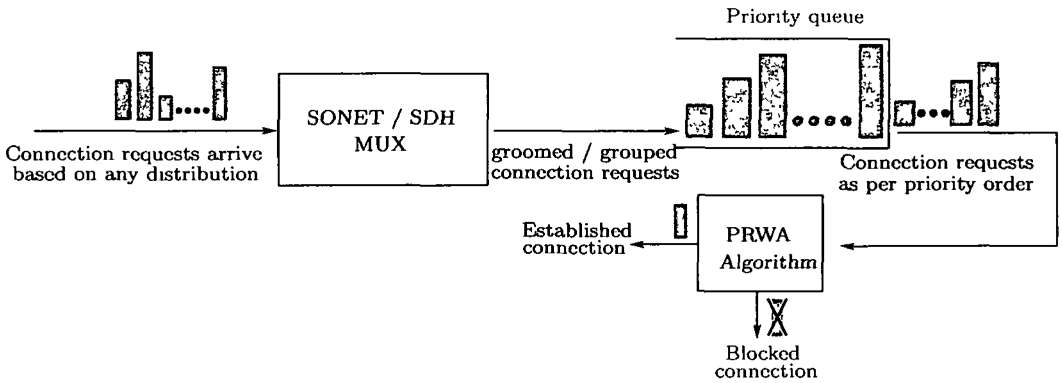


Figure 4-2: Framework of PRWA scheme

As discussed earlier, Figure 4-2 depicts that randomly arrived connection requests are groomed first and then they are enqueued in the priority queue based on their priority order estimated by Algorithm 1. Finally, these groomed connection requests are served for RWA purpose according to their priority order as per Algorithm 2. The details of two steps of PWRA scheme are presented in the following subsections.

4.4.1 Grooming of Connection Requests and Priority Order Estimation

The aim of connection requests grooming is to enhance the effective channel utilization of a given capacity optical network. The motivation of priority order estimation is to give preference to higher priority groomed connection requests

Algorithm 1: Connection requests grooming and priority estimation (CRGPE)

Input: Network configuration and set of connection requests
Output: Groomed connection requests with their priority order

Step 1: Connection requests having the same source-destination pair are groomed within channel capacity according to bandwidth constraint.

$$R = \left\{r_1^{s,d}, r_2^{s,d}, \cdots, r_Z^{s,d}\right\} \mid \sum_{s,d} B(r_i^{s,d}) = B(gr^{s,d})$$

where, R is the set of connection requests and $B(r_i^{s,d})$ indicates the bandwidth requirement of the i^{th} connection request, $r_i^{s,d}$ from source s to destination d. $B(gr^{s,d})$ represents the bandwidth requirement of groomed connection request, $gr^{s,d}$ from source s to destination d.

Step 2: Enqueue the groomed connection requests in the priority queue based on their priority orders estimated by following step 3

Step 3: Grouping the groomed connection requests into two categories, such as, direct physical link groomed connection requests and in-direct physical link groomed connection request.

$$GR_1 = \left\{gr_{D,1}^{s_1,d_1}, gr_{D,2}^{s_2,d_2}, \cdots, gr_{D,X}^{s_X,d_X}\right\}$$
$$GR_2 = \left\{gr_{I,1}^{s_1,d_1}, gr_{I,2}^{s_2,d_2}, \cdots, gr_{I,U}^{s_U,d_U}\right\}$$

such that

$$Vol(gr_{D,1}^{s_1,d_1}) \geq Vol(gr_{D,2}^{s_2,d_2}) \geq \cdots \geq Vol(gr_{D,X}^{s_X,d_X})$$
$$Vol(gr_{I,1}^{s_1,d_1}) \geq Vol(gr_{I,2}^{s_2,d_2}) \geq \cdots \geq Vol(gr_{I,U}^{s_U,d_U})$$

where, GR_1 and GR_2 are the two ordered set of groomed connection requests having direct and indirect physical link, respectively. The priority order of each groomed connection request is assigned according to their positions either in GR_1 or in GR_2. Groomed connection requests in GR_1 have higher priorities compared to groomed connection requests in GR_2. $gr_{D,i}^{s_i,d_i}$ and $gr_{I,i}^{s_i,d_i}$ represent the i^{th} groomed connection requests in GR_1 and GR_2, respectively. $Vol(gr_{D,i}^{s_i,d_i})$ and $Vol(gr_{I,i}^{s_i,d_i})$ indicate the volume of traffic for the groomed connection request of $gr_{D,i}^{s_i,d_i}$ and $gr_{I,i}^{s_i,d_i}$, respectively.

in order to maximize the number of established lightpaths. As a result, the call blocking in the network is drastically reduced with incorporation of traffic grooming mechanism and prioritization concept with RWA approach. It has been observed from the literature survey that most of the works [61, 69, 83–85] on traffic grooming have focused on hop-wise grooming of the lightpath. Hop-wise traffic grooming requires optical-electrical-optical (O/E/O) conversion at each hop of the end-to-end path, which leads to increase in both the cost of the network and traffic delay. Therefore in PRWA scheme, we initially groomed connection requests (as per bandwidth) having same source-destination pair with SONET STS multiplexer to avoid intermediate O/E/O conversion. The priority order of each groomed connection request is estimated based on the following two criteria: (i) types of path (direct link or in-direct link physical path) and (ii) volume of traffic. Using these criteria, direct link groomed connection requests are always given higher priority compared to groomed connection requests having in-direct link. Furthermore, the groomed connection requests with direct or in-direct link are arranged in the descending order of their traffic volume. In this work, we have considered that the connection requests to be served by PRWA approach have the same priority in terms of their quality-of-service (QoS) requirement. To achieve our goal, we have considered type of paths and traffic volumes as the criteria for prioritizing of connection requests, which is required due to the wavelength continuity constraint in the network. Wavelength continuity constraint requires use of the same wavelength on all hops in the end-to-end path of a connection. Use of a conventional RWA approach under the wavelength continuity constraint may lead to a situation, where wavelengths may be available but connection requests cannot be established due to unavailability of the required wavelength. Therefore, if the priority order of connection requests is estimated using these criteria, blocking of connection requests due to the affect of wavelength continuity constraint can be reduced to a great extent. This in turn leads to a better performance of the network in terms of lower call blocking, while maintaining the congestion level in the network. The details of connection requests grooming and estimation of their priority order are given in Algorithm 1.

Time complexity analysis of Algorithm 1

The following steps are considered to estimate the overall time complexity.

- The order of time to groom Z connection requests is $O(Z \log Z)$
- The order of time to estimate the length of the priority queue is $O(X + U)$.
- The order of time to group all the groomed connection requests in direct physical link connection requests and indirect physical link connection requests is $O(X \log X + U \log U)$

In the above steps, the first step is the dominating factor. Therefore, the overall time complexity of Algorithm 1 is $\equiv O(Z \log Z)$

Example

For a better understanding of the functionality of Algorithm 1, we explain it with the help of a sample example. For this purpose, we design a sample example network consisting of 6 nodes and 9 bi-directional optical links as depicted in Figure 4-3. Each link has two wavelengths, such as, λ_1 and λ_2. The maximum bandwidth of each wavelength is 1 Gbps. We also assume 18 connection requests as shown in Table 4.2 .

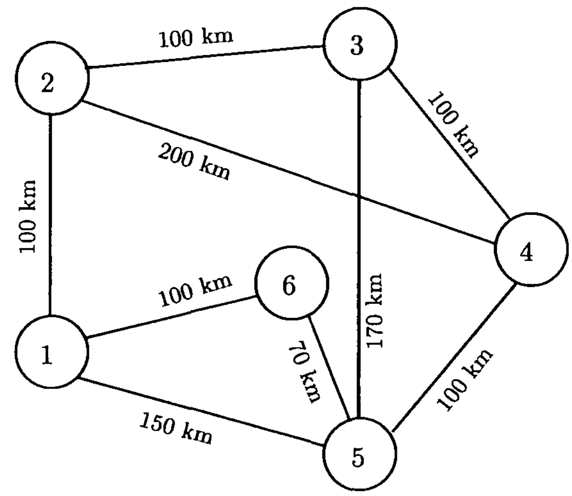


Figure 4-3: Sample example network

Table 4.2: Connection requests with their traffic volume

Connection requests	Traffic (Kbps)	Connection requests	Traffic (Kbps)
$r_1^{1,4}$	2,000	$r_2^{1,2}$	3,000
$r_3^{1,5}$	40,000	$r_4^{1,5}$	20,000
$r_5^{1,4}$	20,000	$r_6^{1,4}$	48,000
$r_7^{1,6}$	300	$r_8^{1,5}$	20,000
$r_9^{1,6}$	40,000	$r_{10}^{1,3}$	24,000
$r_{11}^{1,3}$	70,000	$r_{12}^{1,5}$	30,000
$r_{13}^{1,3}$	7,525	$r_{14}^{1,5}$	30,000
$r_{15}^{1,2}$	9,000	$r_{16}^{1,4}$	30,000
$r_{17}^{1,5}$	5,000	$r_{18}^{1,4}$	40,000

By applying the first step of Algorithm 1, connection requests having the same source-destination pair are groomed within channel capacity (1 Gbps). The

Table 4.3: Groomed connection requests with their traffic volume

Groomed connection requests	Traffic (Kbps)
$gr^{1,4}$	1,40,000
$gr^{1,2}$	12,000
$gr^{1,5}$	1,45,000
$gr^{1,6}$	40,300
$gr^{1,3}$	1,01,525

Table 4.4: Groomed connection requests with their priority

Groomed connection requests	Priority order
$gr^{1,5}$	1^{st}
$gr^{1,6}$	2^{nd}
$gr^{1,2}$	3^{rd}
$gr^{1,4}$	4^{th}
$gr^{1,3}$	5^{th}

groomed connection requests are shown in Table 4.3. Further, as per the third step of Algorithm 1, two grouped order set of groomed connection requests (GR_1 and GR_2) are formed, such that GR_1 ={ $gr^{1,5}$, $gr^{1,6}$, $gr^{1,2}$} and GR_2 ={$gr^{1,4}$, $gr^{1,3}$}. Finally, the priority order of each groomed connection request is estimated and shown in Table 4.4.

4.4.2 Routing and Wavelength Assignment

Routing and wavelength assignment approach is intended to select the best possible end-to-end routes and assign suitable wavelengths to lightpaths for serving connection requests. Here, an attempt is made to choose connection requests as per the priority order in order to reduce the affect of wavelength continuity constraint. The estimation of priority order for groomed connection requests is already illustrated in section 4.4. The details of RWA approach are given in Algorithm 2. In this algorithm (Algorithm 2), K number of shortest end-to-end paths are computed on the basis of link-state information for the entire session of a connection request.

Time complexity analysis of Algorithm 2

The following two steps are considered to estimate the overall time complexity.

- The order of time to compute K shortest end-to-end paths for all the groomed

Algorithm 2: Priority-based routing and wavelength assignment (PRWA)

Input: Set of groomed connection requests according to their priority, GR_1 and GR_2 in priority queue (output from Algorithm 1)

Output: Wavelengths assignment with total number of successful and unsuccessful connections in the network

Step 1: For each groomed connection request, compute K number of shortest end-to-end paths using Dijkstra's algorithm on the basis of link state information

Step 2: For each groomed connection request in GR_1 and GR_2, selected based on their priority order, perform the following in the given sequence:

(a) Try to assign a wavelength according to wavelength constraints to the primary path based on First-fit method.

(b) If no wavelength assignment is possible in step 2(a), consider the alternate paths in the ascending order of their lightpath distance for assigning a wavelength (with similar constraint on wavelength like in step 2(a)) till one alternate path is assigned a wavelength.

(c) If no wavelength assignment is possible either in step 2(a) or step 2(b) within t_H, the groomed connection request is treated as blocked one. Otherwise, calculate the established connections for each groomed connection request and add it to the total number of established connections in the network.

(d) Drop the groomed connection request from the network.

connection requests is $O((E + N \log N + K) \cdot (X + U))$ [89] or $O((N (N - 1) + N \log N + K) \cdot (X + U)) \equiv O(N^2 \cdot (X + U))$

- The order of time to perform wavelength assignment for all the groomed connection requests is $O(L \cdot W \cdot K \cdot (X + U))$ or $O((N - 1) \cdot W \cdot K \cdot (X + U)) \equiv O(N \cdot (X + U))$

In the above steps, the first step is the dominating factor. Therefore, the overall time complexity of Algorithm 2 is $\equiv O(N^2 \cdot (X + U))$

Example

The functionality of Algorithm 2 is explained with the help of the same example as already discussed in section 4.4 The groomed connection requests in GR_1 and GR_2 are severed for RWA approach according to their priority order as shown

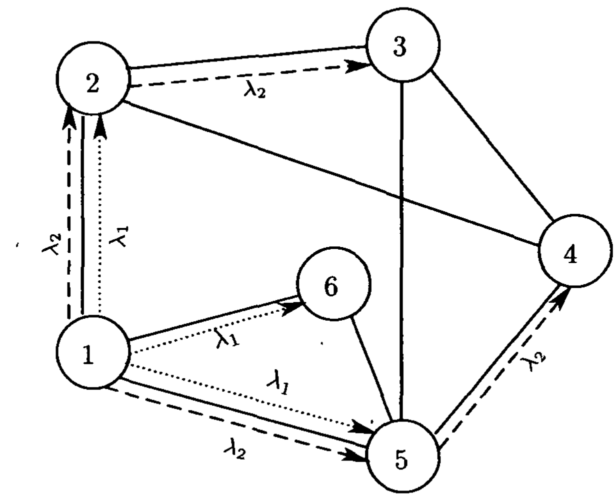


Figure 4-4: Virtual topology of sample example network

in Table 4.4. Finally, the virtual topology of the sample network is formed and depicted in Figure 4-4.

4.5 Performance Analysis

In this section we will present simulation results in two experimental setups to show that PRWA reduces the call blocking while maintaining the congestion level in the network. Our experimental setup consists of 14 nodes with 24 bi-directional physical links of the Indian network and 14 nodes with 21 bi-directional physical links of NSFNET [10] as shown in Figure 3-1 (page number 44) and Figure 3-2 (page number 45), respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are taken as given in Figure 3-1 and Figure 3-2 for configuring the example networks.- the Indian network and NSFNET, respectively.
- The connection requests are generated randomly based on a Poisson process, and the arrival time between two successive requests follows an exponential distribution. We choose the Poisson model because the burstiness of traffic on the backbone is usually suppressed by the huge amount of aggregation of services and the actual traffic distribution remains unknown.
- The holding times of the connection requests are exponentially distributed. For the sake of simplicity, the holding time of all the connection requests

having same source-destination pair are assumed to be same. However, differences in holding times for connection requests having same source-destination pair can be handled by taking the maximum of their holding times (similar to [52]) as the holding time for all of them.

- The maximum bandwidth requirement of a connection is 622.08 Mbps according to SONET OC-12/STS-12 [9].
- The maximum capacity of each wavelength channel is 9953.28 Mbps according to SONET OC-192/STS-192 [9]. Therefore, at a time, each wavelength channel can accommodate a maximum 16 number of connection requests having the same source-destination pair.

We have performed the simulation study of the PRWA scheme under blocking and non-blocking conditions of the network. For this purpose, we generated a number of connection requests varying from 1000 to 5000, distributed randomly among all the possible source-destination pairs. The results have been compared with a similar type of non priority-based routing and wavelength assignment (NPRWA) scheme, where wavelength assignment has been performed based on existing FF method [24].

4.5.1 Blocking Case

Here, we will show the performance of PRWA scheme in terms of blocking probability already defined in chapter 3 (page number 45) under blocking condition of the network. The situation where some connection requests are blocked or rejected due to unavailability of a required wavelength on the end-to-end path is defined as the blocking condition. Initially we determine the optimum number of alternate paths for RWA phase, which trades-off between call blocking and average setup time. Finally, the results are compared with NPRWA for different numbers of connection requests.

Figure 4-5 and Figure 4-6 show blocking probability versus number of wavelengths, obtained by using PRWA scheme in the Indian network and NSFNET, respectively, with 1000 connection requests. In both the figures, K = 1 corresponds to a primary path and other values of K (*i.e.* K >1) represent using K-1 number of alternate paths. It has been revealed that in both the networks, blocking probability decreases with increase in number of wavelengths. On the other hand, blocking probability also decreases with increase in number of

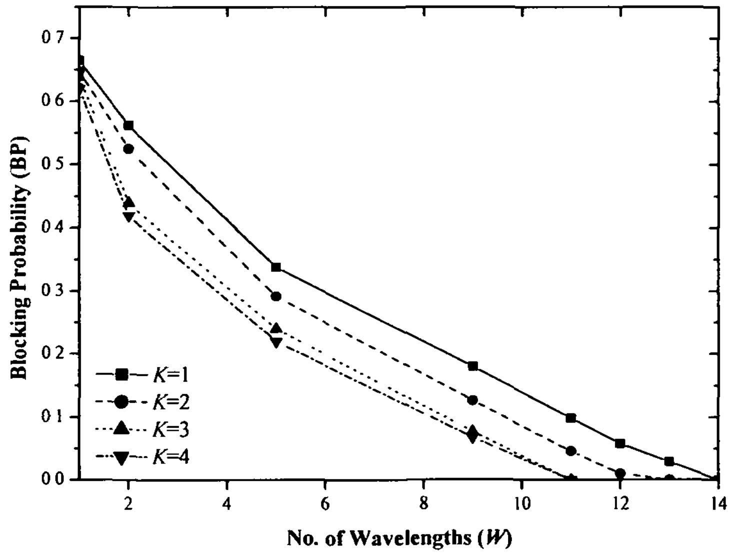


Figure 4-5: BP versus *W*, obtained by using PRWA in the Indian network

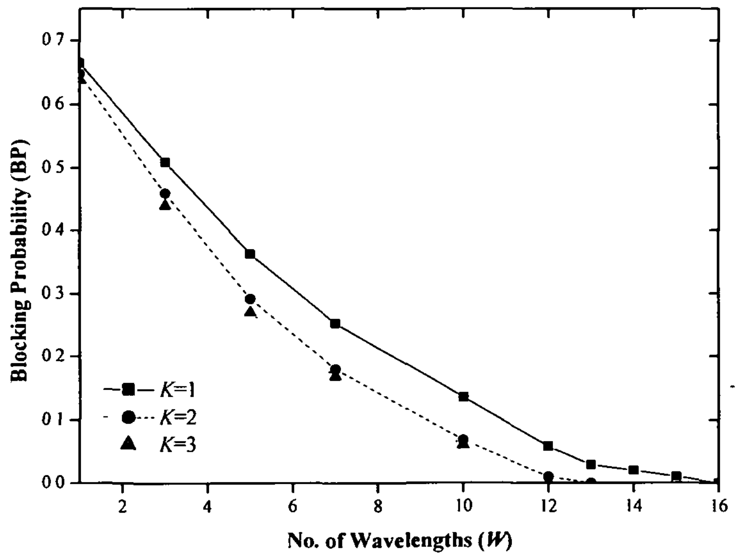


Figure 4-6: BP versus *W*, obtained by using PRWA in NSFNET

paths. The variation of blocking probability with number of wavelengths, using up to three (*i.e.* K=4) alternate paths is close to that of using up to two (*i.e.* K=3) alternate paths in the Indian network. Similarly, in NSFNET, the variation of blocking probability using up to two (*i.e.* K=3) alternate paths is close to that of using up to one (*i.e.* K=2) alternate path. We have already seen from Figure 3-5 (page number 47) and Figure 3-6 (page number 48) in chapter 3 that the average

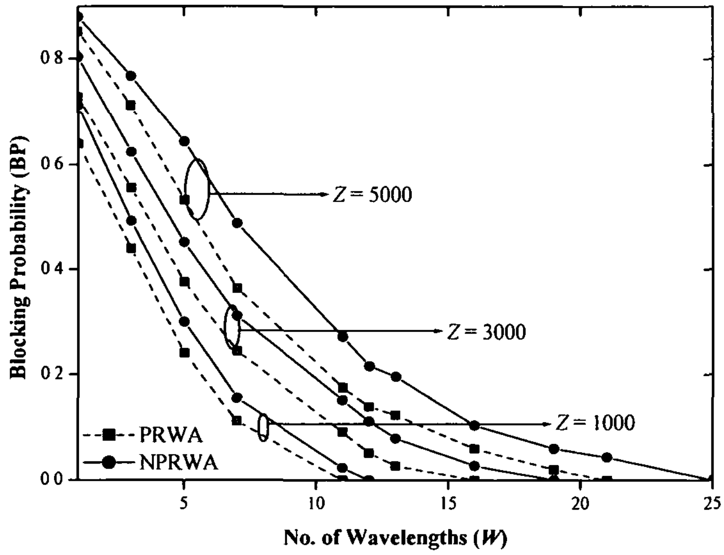


Figure 4-7: BP versus W, obtained by using PRWA and NPRWA, with different numbers of connection requests in the Indian network

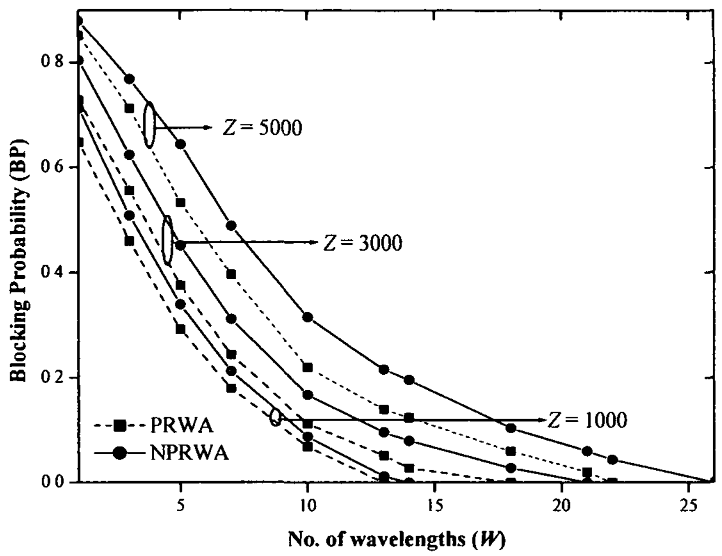


Figure 4-8: BP versus W, obtained by using PRWA and NPRWA, with different numbers of connection requests in NSFNET

setup time increases with increase in number of alternate paths. From the above analysis, we can summarize that as the number of alternate paths increases, the blocking probability decreases and the average setup time increases. Therefore, it is required to trade off between blocking probability and average setup time.

Thus, the number of alternate paths for RWA purpose is considered up to one and two for NSFNET and the Indian network, respectively. The same observation is being used for further analysis of PRWA scheme.

We have also studied the blocking probability using both the PRWA and NPRWA schemes with different number of connection requests in the Indian network and NSFNET as depicted in Figure 4-7 and Figure 4-8, respectively. It has been observed from the figures that the blocking probability using PRWA scheme is less than that of using NPRWA scheme for all the number of connection requests. This is because of incorporation of prioritization concept in the PRWA scheme. It is evident from Figure 4-7 and Figure 4-8 that the blocking probability increases with increase in number of connection requests. Furthermore, it can be seen that the blocking probability in the Indian network is less than that in NSFNET. This is mainly because of consideration of more number of alternate paths in the Indian network compared to NSFNET.

4.5.2 Non Blocking Case

Here, we will show the performance of PRWA scheme in terms of congestion level and total number of used wavelengths to achieve the non-blocking condition in the network. The situation where all the connection requests are successfully assigned lightpaths is defined as the non-blocking condition. The virtual topologies of the networks are constructed to show the traffic distribution on the lightpaths. The results are compared with NPRWA for different numbers of connection requests.

Figure 4-9 and Figure 4-10 show the virtual topology of the Indian network and NSFNET, respectively. The virtual topology of both the networks has been constructed using PRWA scheme with 1000 connection requests. Table 4.5 shows the used wavelengths for establishment of lightpaths during the constructing of virtual topology of the Indian network. We have estimated the number of required wavelengths for different number of connection requests using PRWA and NPRWA schemes under non-blocking condition of the networks. Figure 4-11 and Figure 4-12 depict the number of wavelengths versus number of connection requests, obtained by using PRWA and NPRWA schemes in the Indian network and NSFNET, respectively. It can be observed from the Indian network that 11, 16 and 21 numbers of wavelengths are required to establish 1000, 3000, and 5000 number of connection requests using PRWA scheme. To establish the same number of connection requests in the Indian network using NPRWA scheme require 12,

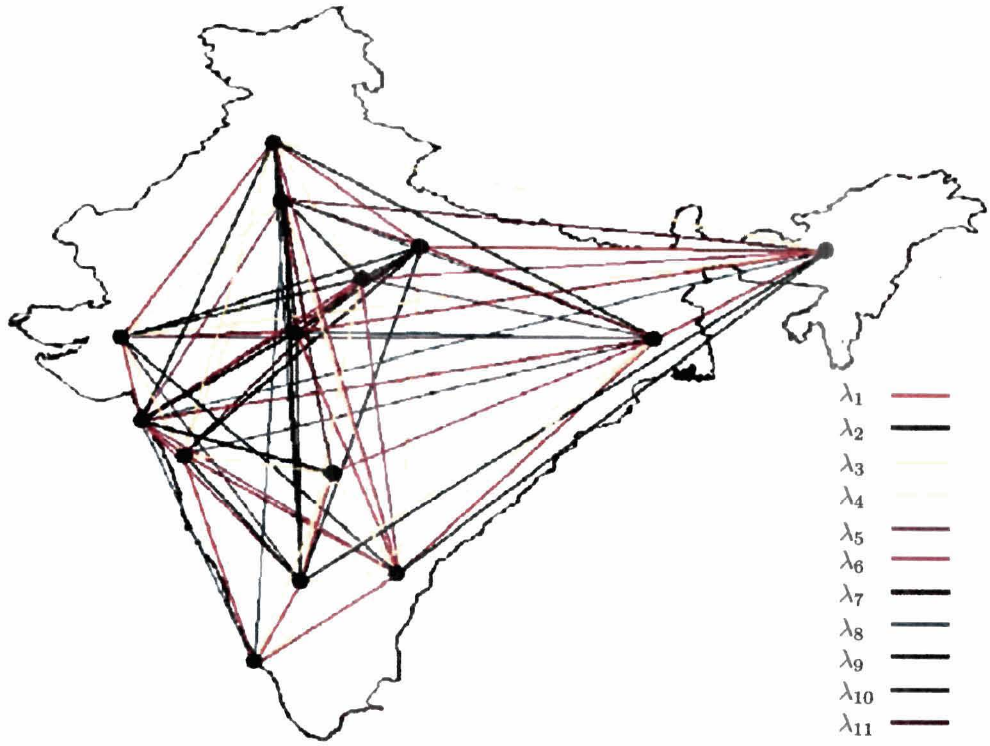


Figure 4-9: Virtual topology of the Indian network, obtained by using PRWA scheme

19 and 25 number of wavelengths, respectively. Similarly, it can be observed from NSFNET that 14, 21 and 25 numbers of wavelengths are required to establish 1000, 3000, and 5000 number of connection requests using NPRWA scheme. However, 13, 17 and 22 number of wavelengths are required to establish the same number of connection requests in NSFNET using PRWA scheme. It can be seen from Figure 4-11 and Figure 4-12 that as the number of connection requests increases, the rate of increase in number of wavelengths using PRWA scheme is less than that of using NPRWA scheme. The similar type of results is obtained in NSFNET as depicted in Figure 4-12. However, the required number of wavelengths under non-blocking condition in NSFNET is slightly higher than that in the Indian network due to consideration of more number of alternate paths. From the analysis of Figure 4-11 and Figure 4-12, it can be summarized that the PRWA scheme outperforms the NPRWA scheme as the number of connection requests increases in the networks. We have already observed in chapter 3 that for serving 5000 connection requests, a large number (~350) of wavelengths is required without incorporation of traffic grooming. However, ~25 numbers of wavelengths are required to establish the same number of connection requests using NPRWA scheme which is ~14 times less than that of without incorporation of traffic grooming mechanism.

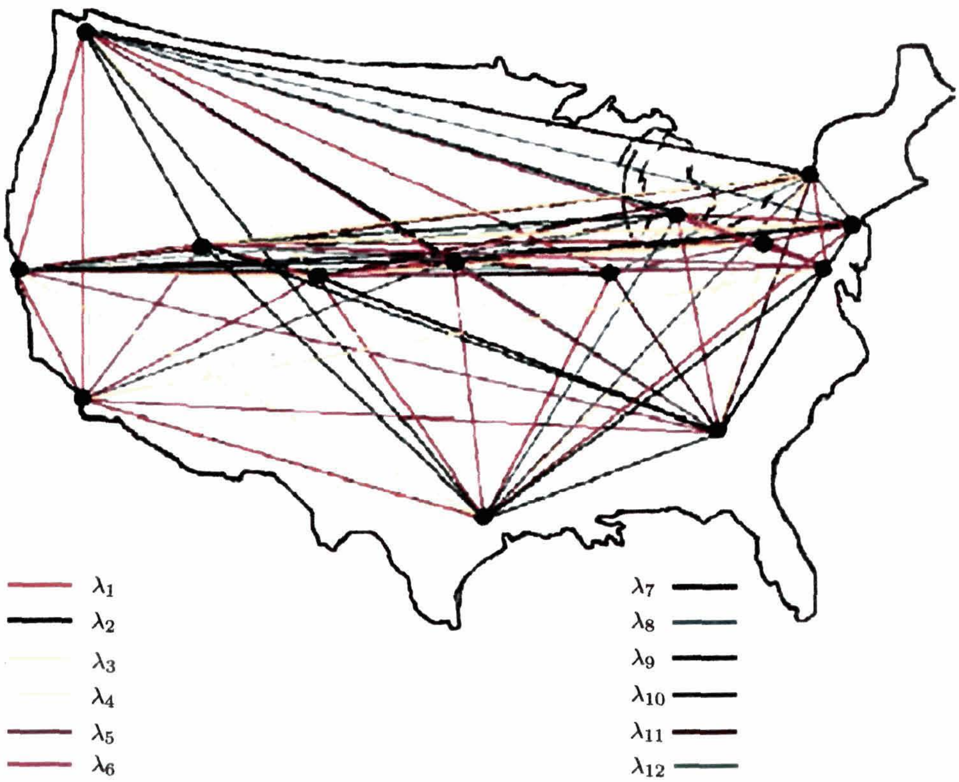


Figure 4-10: Virtual topology of the NSFNET, obtained by using PRWA scheme

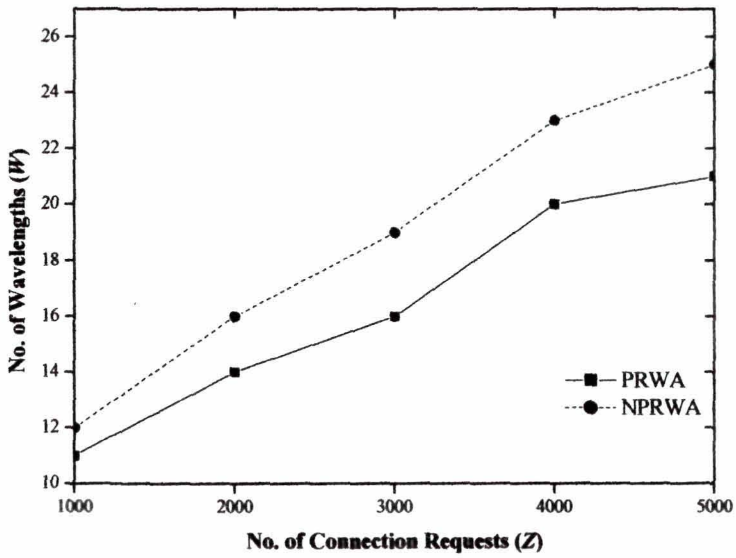


Figure 4-11: *W* versus *Z*, obtained by using PRWA and NPRWA in the Indian network

Table 4.5: Lightpaths and used wavelengths for constructing the virtual topology of the Indian network

s-d pair	Path	Wavelength	s-d pair	Path	Wavelength
1-4	1-4	λ_1	709-2	9-3-2	λ_4

1-5	1-5	λ_1	11-7	11-12-8-7	λ_3
2-1	2-1	λ_1	7-14	7-8-14	λ_4
2-3	2-3	λ_1	5-2	5-1-2	λ_5
2-6	2-6	λ_1	2-8	2-6-7-8	λ_5
3-2	3-2	λ_1	7-11	7-8-12-11	λ_6
3-4	3-4	λ_1	14-13	14-12-13	λ_4
3-9	3-9	λ_1	5-12	5-13-12	λ_2
3-10	3-10	λ_1	12-9	12-11-9	λ_3
4-1	4-1	λ_1	2-12	2-1-5-13-12	λ_4
4-3	4-3	λ_1	7-3	7-6-5-4-3	λ_4
4-5	4-5	λ_1	13-8	13-12-8	λ_5
5-1	5-1	λ_1	8-13	8-12-13	λ_5
5-4	5-4	λ_1	3-8	3-4-5-6-7-8	λ_7
5-6	5-6	λ_1	12-5	12-13-5	λ_6
5-10	5-10	λ_1	13-1	13-5-1	λ_7
5-13	5-13	λ_1	2-11	2-1-5-13-11	λ_5
6-2	6-2	λ_1	2-14	2-1-5-13-12-14	λ_6
6-5	6-5	λ_1	12-4	12-13-5-4	λ_8
6-7	6-7	λ_1	5-11	5-13-11	λ_7
7-6	7-6	λ_1	9-6	9-3-4-5-6	λ_5
7-8	7-8	λ_1	9-13	9-11-13	λ_3
7-9	7-9	λ_1	5-8	5-6-7-8	λ_8
8-7	8-7	λ_1	9-8	9-7-8	λ_9
8-12	8-12	λ_1	2-5	2-1-5	λ_7
8-14	8-14	λ_1	11-8	11-12-8	λ_4
9-3	9-3	λ_1	10-8	10-5-6-7-8	λ_{10}
9-7	9-7	λ_1	12-2	12-13-5-1-2	λ_9
9-10	9-10	λ_1	2-13	2-1-5-13	λ_8
9-11	9-11	λ_1	8-1	8-7-6-5-1	λ_8
10-3	10-3	λ_1	11-4	11-13-5-4	λ_{17}
10-5	10-5	λ_1	10-13	10-5-13	λ_{14}
10-9	10-9	λ_1	3-13	3-4-5-13	λ_{15}
11-9	11-9	λ_1	4-11	4-5-13-11	λ_{16}
11-12	11-12	λ_1	10-12	10-5-13-12	λ_{17}
11-13	11-13	λ_1	4-12	4-5-13-12	λ_{18}
11-14	11-14	λ_1	1-3	1-4-3	λ_7
12-8	12-8	λ_1	2-9	2-3-9	λ_3
12-11	12-11	λ_1	3-1	3-4-1	λ_8
12-13	12-13	λ_1	5-7	5-6-7	λ_6
12-14	12-14	λ_1	14-3	14-12-13-5-4-3	λ_{18}
13-5	13-5	λ_1	14-6	14-8-7-6	λ_9
13-11	13-11	λ_1	10-6	10-5-6	λ_3
13-12	13-12	λ_1	3-7	3-4-5-6-7	λ_{13}
14-8	14-8	λ_1	8-4	8-7-6-5-4	λ_{10}
14-11	14-11	λ_1	12-6	12-8-7-6	λ_{11}
14-12	14-12	λ_1	3-5	3-4-5	λ_{10}
7-2	7-6-2	λ_2	11-6	11-12-8-7-6	λ_{12}

8-9	8-7-9	λ_2	4-14	4-5-13-12-14	λ_{19}
7-1	7-6-5-1	λ_3	6-14	6-7-8-14	λ_{12}
13-9	13-11-9	λ_2	14-9	14-11-9	λ_5
1-11	1-5-13-11	λ_3	9-14	9-11-14	λ_5
7-12	7-8-12	λ_2	3-12	3-4-5-13-12	λ_{20}
9-1	9-3-4-1	λ_2	4-2	4-1-2	λ_3
9-4	9-3-4	λ_3	6-11	6-7-8-12-11	λ_{14}
1-7	1-5-6-7	λ_2	6-4	6-5-4	λ_2
9-12	9-11-12	λ_2	14-7	14-8-7	λ_4
12-1	12-13-5-1	λ_2	10-7	10-5-6-7	λ_9
1-9	1-4-3-9	λ_2	6-12	6-7-8-12	λ_{15}
11-1	11-13-5-1	λ_4	12-7	12-8-7	λ_6
13-14	13-12-14	λ_3	11-2	11-12-8-7-6-2	λ_{18}
13-3	13-5-4-3	λ_3	4-9	4-3-9	λ_9
3-11	3-4-5-13-11	λ_9	11-5	11-13-5	λ_5
14-2	14-12-13-5-1-2	λ_{10}	10-2	10-3-2	λ_2
2-7	2-6-7	λ_3	3-6	3-4-5-6	λ_4
12-10	12-13-5-10	λ_{11}	13-7	13-12-8-7	λ_7
13-6	13-5-6	λ_{12}	2-4	2-1-4	λ_3
11-10	11-9-10	λ_4	8-5	8-7-6-5	λ_5
10-11	10-9-11	λ_4	9-5	9-3-4-5	λ_6
1-8	1-5-6-7-8	λ_{11}	5-9	5-4-3-9	λ_5
13-4	13-5-4	λ_{13}	14-5	14-12-13-5	λ_{14}
7-5	7-6-5	λ_6	7-10	7-6-5-10	λ_7
5-14	5-13-12-14	λ_{10}	3-14	3-4-5-13-12-14	λ_{11}
2-10	2-3-10	λ_2	11-3	11-13-5-4-3	λ_{15}
1-14	1-5-13-12-14	λ_{12}	1-13	1-5-13	λ_{13}
5-3	5-4-3	λ_6	12-3	12-13-5-4-3	λ_{16}
1-12	1-2-6-7-8-12	λ_{16}	4-13	4-3-9-11-13	λ_{19}
14-10	14-8-7-9-10	λ_{14}	6-10	6-5-10	λ_9
14-4	14-12-13-5-4	λ_{19}	10-4	10-3-4	λ_{12}
6-3	6-5-4-3	λ_{11}	8-10	8-7-6-5-10	λ_{13}
4-10	4-3-10	λ_8	4-8	4-5-6-7-8	λ_{17}
6-8	6-7-8	λ_{18}	8-6	8-7-6	λ_{15}
4-13	4-5-13	λ_{10}	8-2	8-7-6-2	λ_{16}
13-2	13-5-1-2	λ_{20}	8-3	8-7-6-5-4-3	λ_{20}
14-1	14-8-7-6-5-1	λ_{17}	4-6	4-1-5-6	λ_{15}
4-7	4-1-5-6-7	λ_{19}	10-1	10-3-4-1	λ_{14}
1-10	1-4-3-10	λ_{10}	6-1	6-5-1	λ_{12}
8-11	8-12-11	λ_4	13-10	13-11-9-10	λ_6
6-9	6-7-9	λ_4	6-13	6-7-8-12-13	λ_{20}
1-6	1-5-6	λ_{14}	10-14	10-9-11-14	λ_6
7-13	7-8-12-13	λ_3	7-4	7-6-5-4	λ_{14}

It is also important to study congestion in the network for verification of

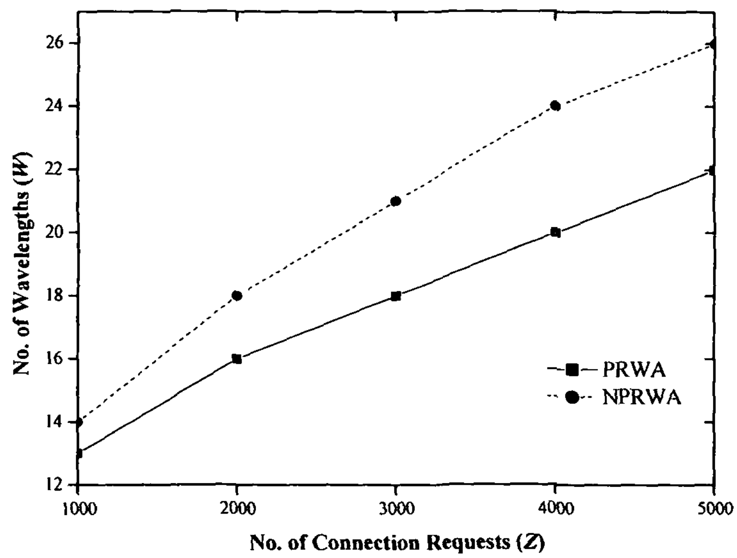


Figure 4-12: W versus Z, obtained by using PRWA and NPRWA in NSFNET

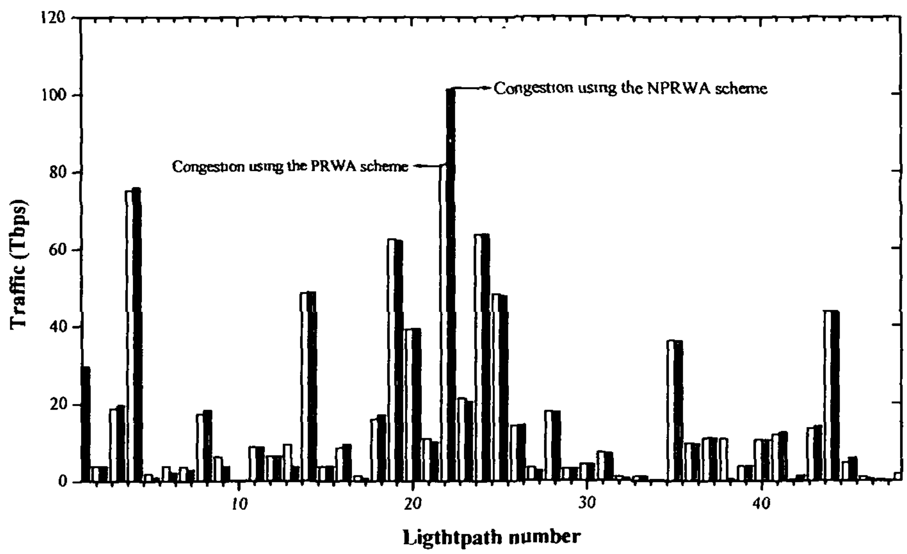


Figure 4-13: Congestion in the Indian network, obtained by using the PRWA and NPRWA schemes

traffic distribution of the lightpaths when the traffic load is very high. Congestion [8] in a network is defined as the maximum traffic flow on any lightpath in the network due to traffic carried between all source-destination pairs. The traffic offered onto a lightpath is obtained as a sum of the traffic offered onto the lightpath due to all the node pairs as shown in Equations (4.1) and (4.2). The traffic is routed

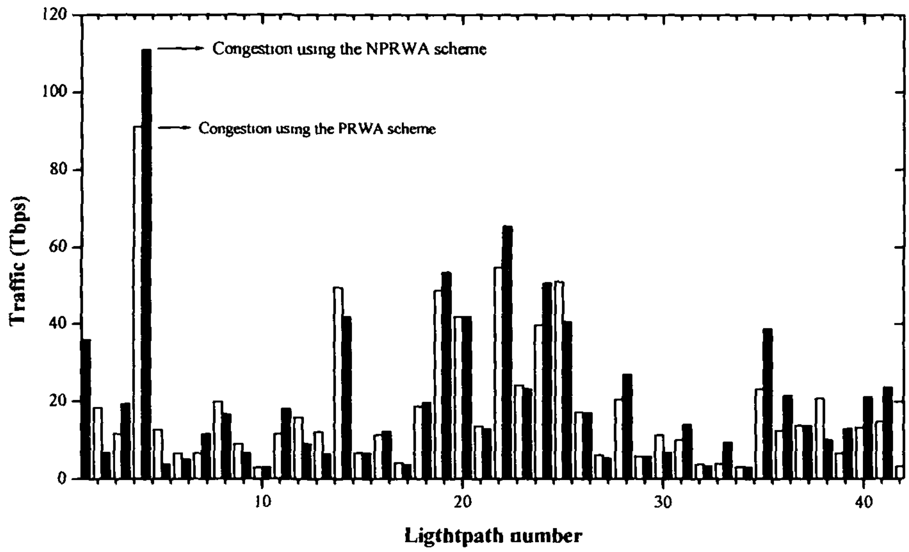


Figure 4-14: Congestion in NSFNET, obtained by using the PRWA and NPRWA schemes

Table 4.6: Lightpath number of corresponding adjoin nodes in the Indian network

Lightpath no	Nodel	Node2	Lightpath no	Nodel	Node2
1	1	2	25	8	7
2	1	4	26	8	12
3	1	5	27	8	14
4	2	1	28	9	3
5	2	3	29	9	7
6	2	6	30	9	10
7	3	2	31	9	11
8	3	4	32	10	3
9	3	9	33	10	5
10	3	10	34	10	9
11	4	1	35	11	9
12	4	3	36	11	12
13	4	5	37	11	13
14	5	1	38	11	14
15	5	4	39	12	8
16	5	6	40	12	11
17	5	10	41	12	13
18	5	13	42	12	14
19	6	2	43	13	5
20	6	5	44	13	11
21	6	7	45	13	12
22	7	6	46	14	8
23	7	8	47	14	8
24	7	9	48	14	12

on both the virtual topologies of the Indian network and NSFNET as depicted in Figure 4-9 and Figure 4-10, respectively, with 1000 number of connection requests. Figure 4-13 and Figure 4-14 show the traffic load on each lightpath between adjacent node pairs in the Indian network and NSFNET, respectively. In the figures, the white bars and black bars represent the traffic offered onto the lightpaths between adjacent node pairs for the PRWA and NPRWA schemes, respectively. The lightpaths number between adjacent node pairs in the Indian network is given in Table 4.6. It can be observed from the Figure 4-13 and Figure 4-14 that the offered traffic on the lightpath number 22 and 4 are the maximum in the Indian network and NSFNET, respectively, for both schemes. Therefore, the congestion in the Indian network and NSFNET is defined on the lightpath number 22 and 4, respectively. However, the congestion of the Indian network using PRWA scheme is ~19% less than that of using NPRWA scheme. This is because using PRWA scheme, the traffic on the lightpath number 22 is distributed evenly across other lightpaths. Similarly, in NSFNET, the congestion using PRWA scheme is ~18% less than that of using NPRWA scheme.

4.6 Conclusion

In this chapter, we have presented a priority-based routing and wavelength assignment (PRWA) scheme with incorporation of traffic grooming mechanism to reduce call blocking, while maintaining the congestion level in the network. In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate O/E/O conversion and then these groomed connection requests are served by a RWA approach according to their priority order. The priority order of each groomed connection request is estimated based on the types of path (direct link physical path or indirect link physical path) and the volume of traffic. The effectiveness of the PRWA scheme has been examined through its performance evaluation in two example optical networks, namely, (i) the Indian network and (ii) NSFNET. From the simulation study we draw the following conclusions:

- It has been found that the congestion in the Indian network and NSFNET is reduced by ~19% and ~18%, respectively, using PRWA scheme for 1000 connection requests.
- It can be observed that the call blocking using PRWA scheme is less than that of using NPRWA scheme.

- We also observed that the number of required wavelengths to achieve non-blocking condition in the network is drastically reduced with incorporation of traffic grooming mechanism as compared to without incorporation of traffic grooming mechanism.

Therefore, PRWA scheme will be an attractive option to reduce the call blocking while maintaining congestion level in practical networks. Till now we have investigated the RWA problem with and without grooming for reducing the call blocking. Quality of service (QoS) is one of the critical design issues in WDM based optical network to maintain the signal quality which has been addressed in the next chapter.

Chapter 5

Priority-based Dispersion-reduced Wavelength Assignment Scheme

5.1 Introduction

In recent years, to fulfill the ever-increasing demand of communication bandwidth, research interests have grown towards the high-speed optical networks. An optical network consists of nodes linked with optical fiber, where dispersion creates the signal distortions during transmission. In a wide-area optical network, dispersion of a signal increases with increase in fiber length which results in degradation of system performance in terms of signal quality. Although, dispersion compensating devices like - dispersion compensating fiber (DCF), optical phase conjugation, pulse prechirping and duobinary transmission have been usually used to reduce dispersion, they are very expensive. As an alternative solution, wavelength assignment scheme can incorporate mechanisms to reduce the overall dispersion in the network. Conventional wavelength assignment approaches, such as, First-fit (FF), Random wavelength assignment (R), Least-used (LU), Most-used (MU), Min-product (MP), Least-loaded (LL), Max-sum (MS) and Relative Capacity Loss (RCL) that have been reported in the literature [8,10,24], are lacking of capability to take care of the reduction of overall dispersion in the network. In this direction, N. Zulkifli *et. al* [90] have proposed a dispersion optimized impairment constraint (DOIC) based RWA to reduce the dispersion in the network. However, in their approach DCF has been used to optimize the dispersion. Use of DCF is not very effective, because DCF is very expensive and its propagation loss is very high compared to Step-index Fiber (SIF). To the best of our knowledge, no priority-based wavelength assignment scheme has been reported without using dispersion compensating devices for improving the overall signal quality in the network.

In this chapter, we have proposed a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme with incorporation of traffic grooming mechanism to improve the overall signal quality in the network. The results have been compared with a similar type of non dispersion-reduced wavelength assignment (NDRWA) scheme. The rest of this chapter is organized as follows. Section 5.2 formally defines the problem and formulates the objective function. In that section, we also address the model assumptions, and define symbols and notations used throughout this chapter. Dispersion-reduced node architecture is presented in section 5.3 along with the functionality of its components. Section 5.4 presents the PDRWA scheme with incorporation of traffic grooming mechanism. Furthermore in that section, we elaborate the working principle of PDRWA scheme with the help of an example. Section 5.5 evaluates the performance of the proposed scheme under blocking and non-blocking conditions. Finally, section 5.6 concludes this chapter.

5.2 Problem Statement

We model the physical topology of an optical network as a connected graph G' (V', E'), where V' and E' are the set of nodes and set of bi-directional optical fiber links in the network, respectively. Here, each link $e \epsilon E'$ has a finite number of wavelengths denoted by W. A non-negative link cost $C(e)$ is assigned to every link e in the network, which represents the distance between the adjacent node pair connected by e. The following assumptions are considered in our model.

5.2.1 Assumptions

- Each fiber link can carry an equal number of wavelengths and the network is without wavelength conversion capabilities.
- All the lightpaths sharing at least one fiber link are allocated distinct wavelengths.
- Each node can work as both an access node and a routing node.
- Each node is equipped with a fixed number of tunable transceivers.

- Each node is capable of multiplexing/demultiplexing as many connection requests having the same source-destination pair as possible within the channel capacity.
- All channels have the same bandwidth.

5.2.2 Notations and Symbols

For the remainder of this chapter, the symbols and notations used are summarized in Table 5.1.

Table 5.1: Used notations and symbols

Notations / Symbols	Comments
N	Total number of nodes in the network
E	Total number of links in the network
Z	Total number of connection requests in the network
Y	Total number of groomed connection requests in the network
r	A connection request
s	The source of a connection request
d	The destination of a connection request
R	Set of all connection requests
GR	Ordered set of all groomed connection requests
W''	Ordered set of wavelengths per fiber link in the increasing order of their dispersion
L	Total number of physical links between a source-destination pair
W	Total number of wavelengths per fiber link
t_H	Holding time of a connection request. This time is supplied by the network designer according to user requirement. The connection request should be established within this time
K	Total number of lightpaths for a connection request
$D(\lambda)$	Coefficient of total dispersion in *ps/(nm.km)* of a wavelength
$D_m(\lambda)$	Coefficient of material dispersion in *ps/(nm.km)* of a wavelength

$D_{wd}(\lambda)$	Coefficient of waveguide dispersion in $ps/(nm.km)$ of a wavelength
N_D	Coefficient of total dispersion in ps/nm of the network
N_L	Coefficient of total propagation loss in dB of the network
$d_{x,y}$	Distance in kilometer between node x and node y, which is an integer value
d_j	Fiber length of the j^{th} hop in kilometer, which is an integer value
$P^i_{x,y}$	Lightpath-link-indicator and its value is 1, if there exists a lightpath from node x to y. Otherwise its value is 0
n_1	Refractive index of the core
n_2	Refractive index of the cladding
c	Speed of light in vacuum
a'	Radius of core
β	Propagation constant
b_i, a_i	Constants related to material oscillator strengths and oscillator wavelengths, respectively
Δf_{opt}	Optical bandwidth
Δf_{el}	Electrical bandwidth
P_s	Total span loss
NF	Erbium doped fiber amplifier (EDFA) noise factor. This mainly represents amplified spontaneous emission (ASE) noise
EXTP	Extinction ratio penalty
P_{in}	Amplifier input power
A_s	Amplification span in kilometer, which is an integer value
N'	Total number of spans
T_B	Bit duration
σ_λ	Spectral width
σ_0	Pulse width
EOP_{PMD}	Power penalty due to PMD (polarization mode dispersion)
EOP	Power penalty due to dispersion
$Q_{withPMD}$	Quality of signal (Q-factor) with PMD effect
$Q_{withoutPMD}$	Quality of signal (Q-factor) without PMD effect

D_{PMD}	Fiber PMD coefficient
N_{PMD}	Total PMD in the network
$r_i^{s_i,d_i}$	The i^{th} connection request between s_i and d_i in R (set of all connection requests)
$B(r_i^{s_i,d_i})$	Bandwidth requirement of connection request, $r_i^{s_i,d_i}$
$B(gr^{s,d})$	Bandwidth requirement of groomed connection request, $gr^{s,d}$ from source s to destination d
B	Channel bit rate
t_w	Source spectral line-width in nm
FL	Fiber length in kilometer

5.2.3 Objective Function

It had been revealed from the literature [51] that the dispersion increases with increase in channel bit rate. Therefore, we have formulated the total dispersion in the network with consideration of channel bit rate. Our objective in this work is to minimize N_D, total dispersion in the network. The value of total dispersion is given in Equation (5.1).

$$|N_D| = \sum_{i=1}^{Z} B \cdot \sum_{x,y} P_{x,y}^i \cdot D(\lambda) \cdot t_w \cdot (d_{x,y} \ mod \ A_s) \tag{5.1}$$

In Equation (5.1), the total dispersion in the network is computed for all the connection requests, such as, $r_1^{s,d}$, $r_2^{s,d}$, $\cdots$, $r_Z^{s,d}$. We use a lightpath-link-indicator for each connection request, which is represented by $P_{x,y}^i$ for connection request, $r_i^{x,y}$.

5.3 Dispersion-reduced Node Architecture

First, we define some basic terms that are used throughout this chapter as well as this dissertation. Dispersion [15] of a wavelength is defined as the pulse spread on a function of wavelength and it is measured in *ps/(nm . km)*. It is the combination of material and waveguide dispersions. Material dispersion, denoted by $D_m(\lambda)$, occurs because the refractive index varies as a function of the optical wavelength.

Waveguide dispersion, denoted by $D_{wd}(\lambda)$, occurs due to the wavelength dependence of the group velocity on the mode. It had been revealed from the literature [91] that the polarization mode dispersion (PMD) does not play an important role in lower bit rate channel (less than 10 Gbps). Therefore, in this section we do not consider the PMD effect. The detailed analysis of PMD effect for higher bit rate channels ($\geq$10 Gbps) is given in section 5.5.1. The amount of total dispersion in optical fiber can be represented as given in Equation (5.2).

$$|D(\lambda)| = |D_m(\lambda)| + |D_{wd}(\lambda)| \tag{5.2}$$

where

$$D_m(\lambda) = \frac{\lambda}{c} \cdot \frac{d^2(n_1)}{d\lambda^2} \tag{5.3}$$

$$D_{wd}(\lambda) = -\frac{2(n_1 - n_2)u^2}{c\lambda v^2}\left(1 - \frac{\lambda}{n_2} \cdot \frac{d(n_2)}{d\lambda}\right) \tag{5.4}$$

$$a'^2 = \frac{\lambda^2 v^2}{4\pi^2 \left(n_1^2 - \beta^2\right)} \tag{5.5}$$

$$u^2 = a'^2 \left(\frac{4\pi^2}{\lambda^2} \cdot n_1^2 - \beta^2\right) \tag{5.6}$$

For the following three equations, the value of j is 1 and 2.

$$n_j = \sqrt{1 + \sum_{i=1}^{3} \frac{b_i \lambda^2}{\lambda^2 - a_i^2}} \tag{5.7}$$

$$\frac{d(n_j)}{d\lambda} = -\frac{\lambda}{n_j} \sum_{i=1}^{3} \frac{a_i^2 b_i}{\left(\lambda^2 - a_i^2\right)^2} \tag{5.8}$$

$$\frac{d^2(n_j)}{d\lambda^2} = -\sum_{i=1}^{3} \frac{a_i^2 b_i}{(\lambda^2 - a_i^2)^2 \cdot n_j} \left[\frac{(a_i^2 + 3\lambda^2)}{(\lambda^2 - a_i^2)} + \frac{\lambda^2 \sum_{i=1}^{3} \frac{a_i^2 b_i}{(\lambda^2 - a_i^2)^2}}{(n_j)^2}\right] \tag{5.9}$$

In order to reduce the total dispersion in optical network, a network node is being designed to switch the optical signals as per the PDRWA scheme which

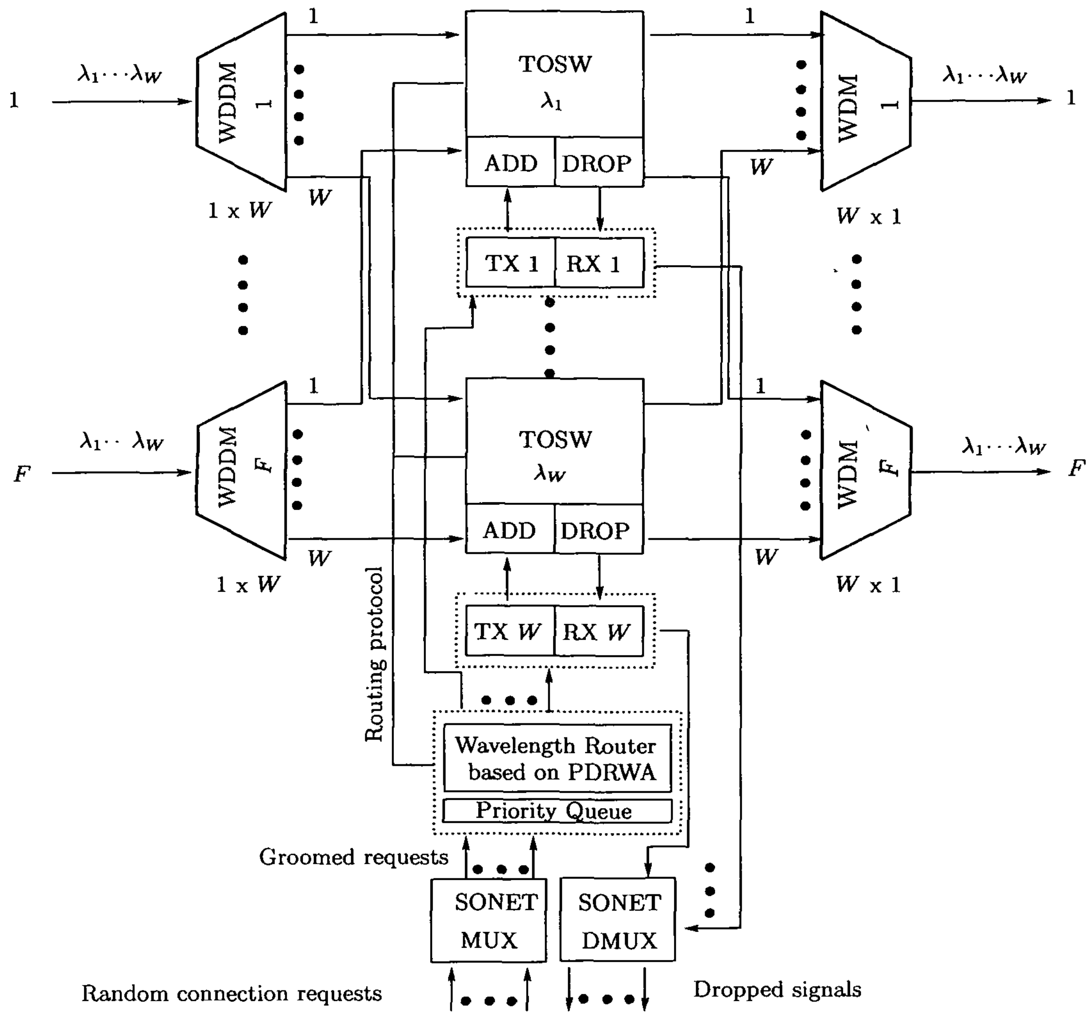


Figure 5-1: Dispersion-reduced node architecture

will be explained in section 5.4. Figure 5-1 shows the logical architecture of a dispersion-reduced node which uses a number of devices, these are (i) F number of wavelength division multiplexers (WDMs) / wavelength division demultiplexers (WDDMs), (ii) W number of thermo-optic switches (TOSWs), (iii) W number of transmitters (TXs), (iv) W number of receivers (RXs), (iv) W number of add-drop multiplexers (ADMs), (v) a SONET STS multiplexer / SONET STS demultiplexer and (vi) a wavelength router based on PDRWA algorithm. The functions performed by a network node are primarily consist of three tasks. These tasks are similar to the set of tasks performed by a network node in the priority-based routing and wavelength assignment (PRWA) scheme already explained in chapter 4 (page number 56). These tasks are briefly explained as follows:

(i) Initially, connection requests having the same source-destination pair are groomed with SONET STS multiplexer. This end-to-end grooming is similar to the traffic grooming discussed in section 4.4 of chapter 4. Then these groomed connection requests are assigned wavelengths based on their lightpath distance, where connection requests with longer lightpath are assigned the wavelengths having lesser dispersion and vice versa. Transmitters use these assigned wavelengths to generate and transmit optical signals of proper wavelengths. Further, transmitted signals are added to thermo-optic switches through the add-drop multiplexers. Then, the wavelengths are switched by thermo-optic switches. Finally, the wavelengths are multiplexed by wavelength division multiplexers at corresponding output fiber links in order to deliver the signals at destination nodes. This task is accomplished by wavelength router, in accordance with PDRWA algorithm.

(ii) On the other hand, the wavelengths from input fiber links are demultiplexed by wavelength division demultiplexers. The demultiplexed optical signals are switched by thermo-optic switches and finally multiplexed onto the corresponding output fiber link.

(iii) The wavelengths carrying the optical signals for the node itself are dropped through add-drop multiplexers. These dropped signals are demultiplexed by SONET STS demultiplexer in order to provide optical signals to end-users.

5.4 Priority-based Dispersion-reduced Wavelength Assignment

Priority-based dispersion-reduced wavelength assignment scheme has been developed which is intended to reduce the total dispersion in the network without using any dispersion compensating device. In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate optical-electrical-optical (O/E/O) conversion and then these groomed connection requests are served for lightpath establishment according to their priority order. The priority orders of all the groomed connection requests are estimated as per descending order of their primary lightpath lengths. Using this criterion, longer lightpath groomed connection requests are always given higher priority compared to groomed connection requests having shorter lightpath distance. Our goal is to reduce the total dispersion in the network without using dispersion compensating devices. Therefore, the overall signal quality (Q-factor) in the network is improved without substantial increase in network setup cost. To achieve our goal, the groomed connection requests of higher priority (longer lightpath) are assigned the wavelengths having lesser dispersion and the wavelengths having a higher dispersion are assigned to the groomed connection requests with shorter lightpath distance. Use of a conventional wavelength assignment approach may lead to a situation where the groomed connection requests with longer lightpath are assigned the wavelengths having a higher dispersion and the wavelengths having lesser dispersion are assigned to the groomed connection requests with shorter lightpath distance. As a result, the overall dispersion in the network may increase which degrades the signal quality. Therefore, if the priority order of connection requests is estimated using the above criterion and assign the wavelengths with such constraint on dispersion, the overall dispersion in the network can be reduced to a great extent. This in turn leads to better performance of the network in terms of overall signal quality without substantial increase in network setup cost. The details of RWA approach are given in the Algorithm 3. In this algorithm (Algorithm 3), K number of paths are computed on the basis of link-state information for the entire session of a connection request.

Time complexity analysis of Algorithm 3

The following steps are considered to estimate the overall time complexity.

- The order of time to groom Z connection requests is $O(Z \log Z)$
- The order of time to compute K number of the shortest paths for all the groomed connection requests and sort them in descending order of their primary path lengths is $O(((E + N \log N + K) \cdot Y) + Y \log Y)$ [89] or $O(((N(N-1) + N \log N + K) \cdot Y) + Y \log Y) \equiv O((N^2 \cdot Y) + Y \log Y)$
- The order of time to arrange all the wavelengths in the network according to increasing order of their dispersion is $O((W \log W) \cdot E)$ or $O((W \log W) \cdot (N(N-1)) \equiv O(N^2)$
- The order of time to perform wavelength assignment for Y number of groomed connection requests using K alternate paths is $O(L \cdot W \cdot K \cdot Y)$ or $O((N-1) \cdot W \cdot K \cdot Y) \equiv O(N \cdot Y)$

In the above steps, the second step is the dominating factor. Therefore, the overall time complexity of Algorithm 3 is $\equiv O((N^2 \cdot Y) + Y \log Y)$

Algorithm 3: Priority-based dispersion-reduced wavelength assignment (PDRWA)

Input: Network configuration and set of connection requests
Output: Wavelengths assignment and total dispersion of the network

Step 1: The connection requests having the same source-destination pair are groomed within channel capacity.

$$R = \left\{r_1^{s,d}, r_2^{s,d}, \cdots, r_Z^{s,d}\right\} \mid \sum_{s,d} B(r_i^{s,d}) = B(gr^{s,d})$$

where, R is the set of connection requests and $B(r_i^{s,d})$ indicates the bandwidth requirement of i^{th} connection request, $r_i^{s,d}$ from source s to destination d. $B(gr^{s,d})$ represents the bandwidth requirement of groomed connection request, $gr^{s,d}$ from source s to destination d.

Step 2: Enqueue the groomed connection requests in the priority queue based on their priority orders estimated by following step 3.

Step 3: For each groomed connection request, compute K number of the shortest paths (including primary path) on the basis of link-state information and sort them in descending order of their primary path lengths.

$$GR = \left\{gr_1^{s_1,d_1}, gr_2^{s_2,d_2}, \cdots, gr_Y^{s_Y,d_Y}\right\} \mid dis(gr_1^{s_1,d_1}) \geq dis(gr_2^{s_2,d_2}) \geq \cdots \geq dis(gr_Y^{s_Y,d_Y})$$

where, GR is the ordered set of groomed connection requests and the priority orders of groomed connection requests are assigned according to their positions in GR. $dis(gr_i^{s_i,d_i})$ indicates the length of primary lightpath of groomed connection request $gr_i^{s_i,d_i}$.

Step 4: Arrange the wavelengths of each fiber link in the increasing order of their dispersion, estimated using Equations (5.2)-(5.9).

$$W'' = \{\lambda_1, \lambda_2, \cdots, \lambda_W\} \mid D(\lambda_1) \leq D(\lambda_2) \leq \cdots \leq D(\lambda_W)$$

where, W'' is the ordered set of wavelengths and $D(\lambda_i)$ indicates the dispersion of the wavelength, λ_i.

Step 5: For each of the groomed connection request in GR, selected based on their priority order, perform the following in the given sequence:

(a) First, try to assign a wavelength with less dispersion to the primary lightpath.

(b) If no wavelength assignment is possible in step 5(a), consider the alternate paths in the ascending order of their lightpath distance for assigning a wavelength (with similar constraint on dispersion like in step 5(a)) till one alternate path is assigned a wavelength.

(c) If no wavelength assignment is possible either in step 5(a) or step 5(b) within t_H, the groomed connection request is treated as blocked one. Otherwise, compute the dispersion (with the assigned wavelength) for the groomed connection request and add this dispersion to the total dispersion in the network.

(d) Drop the groomed connection request from the network.

Example

For better understanding of the functionality of the PDRWA scheme, we explain it with the help of a sample example network as shown in Figure 5-2. It consists of 6 nodes, 10 directed optical links and each link has three wavelengths (bandwidth 9953.28 Mbps), such as λ_1, λ_2 and λ_3. We assume the dispersions of λ_1, λ_2 and λ_3 as 20, 18 and 19 in [ps/(nm . km)], respectively. We also assume 16

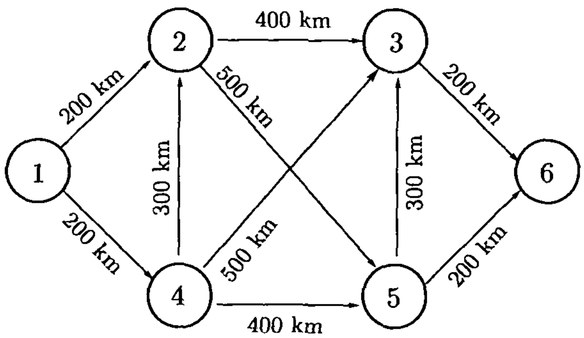


Figure 5-2: Sample example network

randomly generated connection requests whose maximum bandwidth requirement is considered to be within 622.08 Mbps. The set of connection requests is given as $R = \{r_1^{1,2}, r_2^{5,6}, r_3^{4,3}, r_4^{1,6}, r_5^{2,5}, r_6^{1,3}, r_7^{5,3}, r_8^{4,6}, r_9^{1,5}, r_{10}^{2,6}, r_{11}^{1,3}, r_{12}^{4,3}, r_{13}^{4,3}, r_{14}^{4,3}, r_{15}^{1,2}, r_{16}^{1,5}\}$. By applying step 1 of the Algorithm 3, connection requests are groomed within the channel capacity and enqueued them in a queue in their priority order estimated as per the step 3 of the algorithm. The resultant ordered set, $GR = \{gr^{1,6}, gr^{1,5}, gr^{1,3}, gr^{2,6}, gr^{4,6}, gr^{2,5}, gr^{4,3}, gr^{5,3}, gr^{5,6}, gr^{1,2}\}$ is formed. The wavelengths of each fiber links are arranged in the increasing order of their dispersion. Finally, groomed connection requests are established on the basis of priority order as per the constraint on dispersion given in step 5(a) of the Algorithm 3. For comparison purpose, the virtual topologies of the sample network using NDRWA and PDRWA schemes are constructed and depicted in Figure 5-3(a) and 5-3(b), respectively.

5.5 Performance Analysis

In this section we will present simulation results in two experimental setups to show that PDRWA improves the overall signal quality (Q-factor) in the network without substantial increase in network setup cost. Our experimental setup consists of 14 nodes with 24 bi-directional physical links of the Indian network and 14 nodes with 21 bi-directional physical links of NSFNET [10] as shown in Figure 3-1

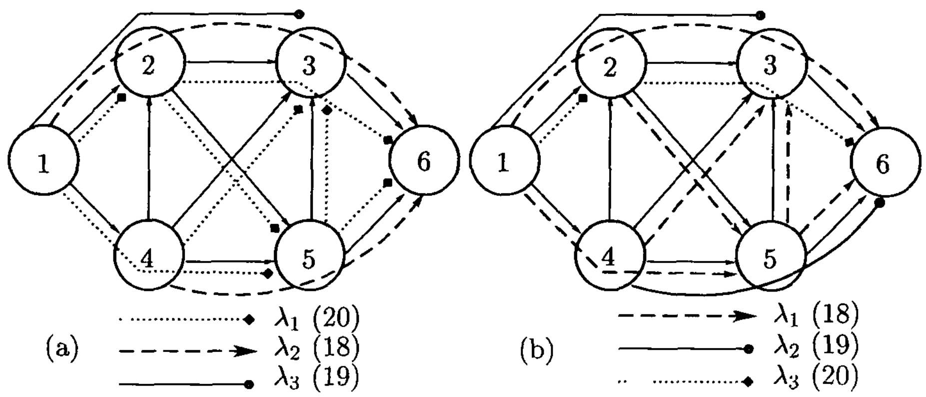


Figure 5-3: Virtual topology of sample example network using (a) NDRWA and (b) PDRWA schemes

(page number 44) and Figure 3-2 (page number 45), respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are taken as given in Figure 3-1 and Figure 3-2 for configuring the example networks - the Indian network and NSFNET, respectively.
- Measurements can be performed on materials contemplated for core GeO_2:86.5 SiO_2 compositions and for claddings Quenched SiO_2, respectively, [92] as shown in Table 5.2.
- Wavelength range considered is from 1.520 μm to 1.590 μm due to its lower propagation loss.
- The spacing between two wavelengths is taken as 0.8 nm for 100 GH_z frequency spacing according to ITU G.694.1 [93].
- The connection requests are generated randomly based on a Poisson process, and the arrival time between two successive requests follows an exponential distribution. We choose the Poisson model because the burstiness of traffic on the backbone is usually suppressed by the huge amount of aggregation of services and the actual traffic distribution remains unknown.
- The holding times of the connection requests are exponentially distributed. For the sake of simplicity, the holding time of all the connection requests having same source-destination pair are assumed to be same. However, differences in holding times for connection requests having same source-destination pair can be handled by taking the maximum of their holding times (similar to [52]) as the holding time for all of them.

- The maximum bandwidth requirement of a connection is 622.08 Mbps according to SONET OC-12/STS-12 [9].

- As the quality of the signal (Q-factor) varies with channel speed, we consider wavelength channels having three different capacities [9], such as, 10 Gbps (OC-192/STS-192), 40 Gbps (OC-768/STS-768) and 100 Gbps, respectively. For these capacities, each wavelength channel can respectively accommodate a maximum 16, 64 and 160 number of connection requests belonging to the same source-destination pair.

- The used system parameters are summarized in Table 5.3.

Table 5.2: Fitted sellmeier coefficients for light guide glasses

Sample	b_1	b_2	b_3	a_1	a_2	a_3
13.5 GeO_2:86.5 SiO_2	0.711040	0.451885	0.704048	0.064270	0.129408	9.425478
Quenched SiO_2	0.696750	0.408218	0.890815	0.069066	0.115662	9.900559

Table 5.3: System parameters and their values in our models

Parameter	Value
EXTP	20 dB [94]
Δf_{opt}	100 GH_z
σ_λ	70 nm
NF	5 dB [95]
σ_0	50 ps [96]
Average span loss in SIF	23 dB [97]
Average span loss in DCF	13 dB [98]
EDFA interval in SIF	100 km [99]
EDFA interval in DCF	15 km [99]
Propagation loss in SIF	0.2 dB/km [100]
Propagation loss in DCF	0.6 dB/km [100]
D_{PMD} for SIF	0.05 $ps/\sqrt{km}$ [95]
D_{PMD} for DCF	0.1 $ps/\sqrt{km}$ [101]

We have performed the simulation study of the PDRWA scheme with connection requests varying from 1000 to 5000, distributed randomly among all the possible source-destination pairs. The results have been compared with a similar type of non dispersion-reduced wavelength assignment (NDRWA) scheme, where wavelength assignment is performed based on existing FF method [24]. For our simulation study, we have estimated the dispersion of SIF using Equations (5.2)-(5.9) as shown in Figure 5-4. In this figure, we have incorporated the experimental results of dispersion in DCF developed by PureGuide®[102]. It has been

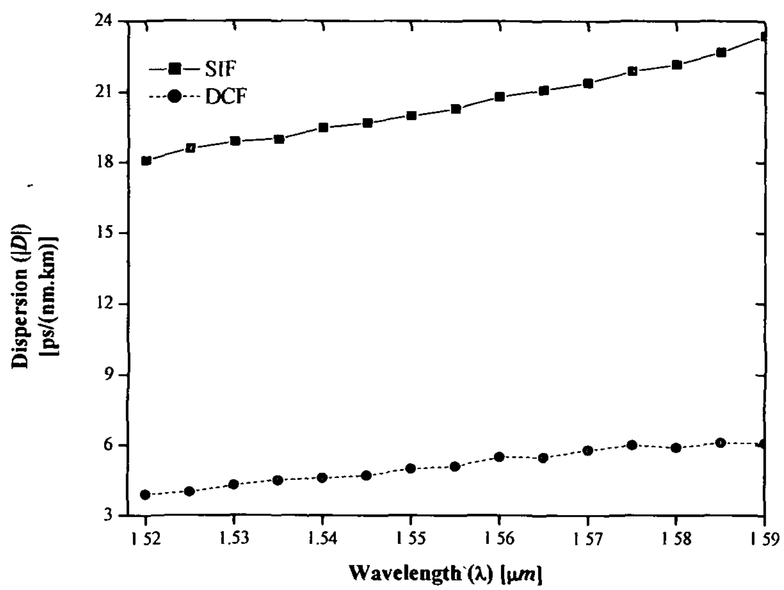


Figure 5-4: Dispersion versus wavelength for SIF and DCF

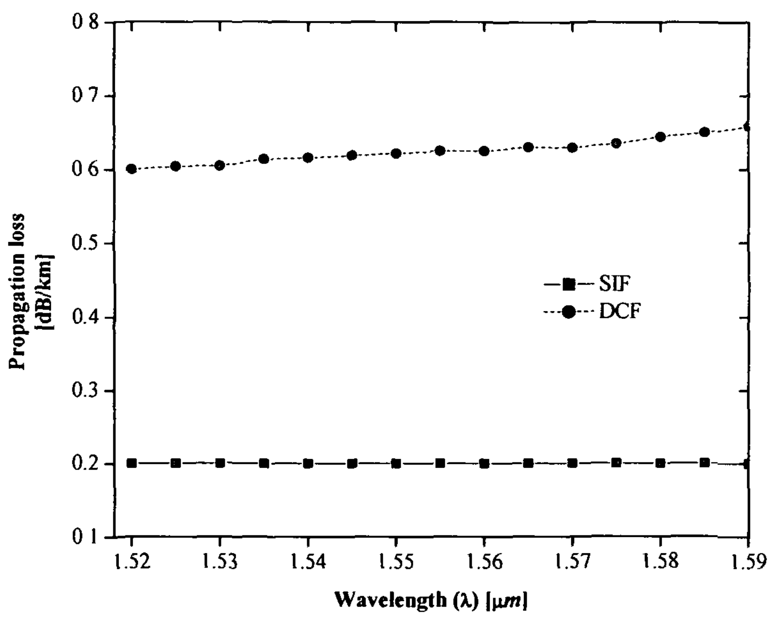


Figure 5-5: Propagation loss versus wavelength for SIF and DCF

observed from Figure 5-4 that the dispersion using SIF increases with increase in wavelength, but it is almost constant for DCF. Although, it can be found from Figure 5-4 that the dispersion using DCF is lower than that of using SIF, the propagation loss using DCF is much higher than that of using SIF (as depicted in Figure 5-5). Therefore, we use SIF with the PDRWA scheme and compare the same with DCF.

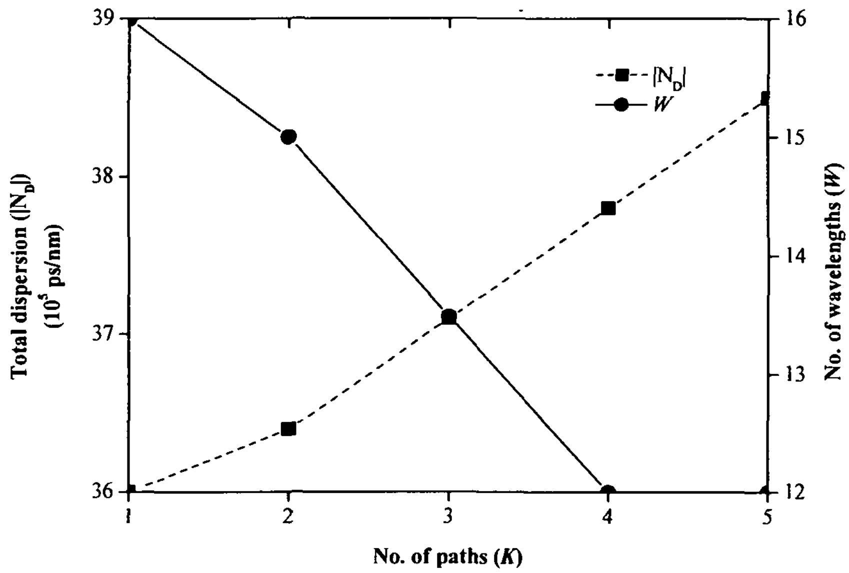


Figure 5-6: Dependence of $|N_D|$ and W on K, obtained by using PDRWA in the Indian network with 10 Gbps channel speed

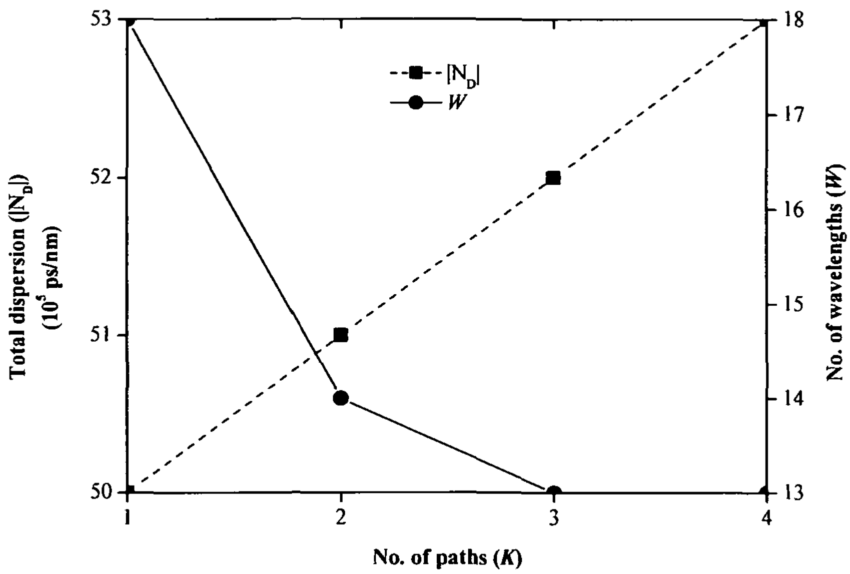


Figure 5-7: Dependence of $|N_D|$ and W on K, obtained by using PDRWA in NSFNET with 10 Gbps channel speed

Figure 5-6 and Figure 5-7 show the dependence of dispersion and the number of wavelengths on the number of paths, obtained by using PDRWA in the Indian network and NSFNET, respectively. For this simulation study, we have generated 3000 number of connection requests with the channel speed is considered as 10 Gbps. In both the figures, $K = 1$ corresponds to a primary path and other values of K (*i.e.* $K > 1$) represent using K-1 number of alternate paths. It is evident from both the networks that the number of wavelengths decreases with increase in number of paths. This is because more paths are used to establish connection requests successfully. It has been observed from both the figures, Figure 5-6 and Figure 5-7 that as the number of paths increases, total dispersion also increases due to increase in lightpath length. The number of wavelengths and total dispersion of the network cross each other, when the number of paths (*i.e.* K value) is considered up to 2 and 3 for NSFNET and the Indian network, respectively. The K value in the Indian network is greater than that in NSFNET due to the presence of more number of bi-directional optical links in the Indian network compared to NSFNET. We have already observed in Figure 3-5 (page number 47) and Figure 3-6 (page number 48) of chapter 3 that the average setup time increases with increase in number of paths. Furthermore, we have also observed that for higher bit rate channel, like - 40 Gbps and 100 Gbps, K values remain almost the same. Therefore, the number of alternate paths for RWA purpose is considered up to one (*i.e.* $K = 2$) and two (*i.e.* $K = 3$), respectively, for NSFNET and the Indian network. The same observation is being used for further analysis of PDRWA scheme.

5.5.1 Non Blocking Case

Here, we will show the performance of PDRWA scheme in terms of total dispersion and total propagation loss in the network under non-blocking condition. The results are compared with NPDRWA for different channel speeds.

Figure 5-8 and Figure 5-9 show total dispersion versus number of connection requests, obtained by using PDRWA and NDRWA schemes respectively in the Indian network and NSFNET with different channel data speeds, such as, 10, 40 and 100 Gbps. It is evident from both the networks that the total dispersion increases with increase in channel bit rates. However, the rate of increase in total dispersion using PDRWA scheme is less than that of using NDRWA scheme. This is because in PDRWA, the connection requests with longer lightpath are assigned to the wavelengths having lesser dispersion and vice versa. Furthermore, it can be observed from both Figure 5-8 and Figure 5-9 that the total dispersion in NSFNET is higher than that in the Indian network. This is because total lightpath distance in NSFNET is more than that in the Indian network.

Total propagation loss versus number of connection requests with 10 Gbps channel speed in the Indian network and NSFNET are depicted in Figure 5-10 and Figure 5-11, respectively. It is evident in both networks that the variation of total propagation loss with number of connection requests using PDRWA scheme is almost close to that of using NDRWA scheme. From the above analysis, we can summarize that the total dispersion significantly reduces by using PDRWA scheme without increasing total propagation loss in the network irrespective of channel speeds.

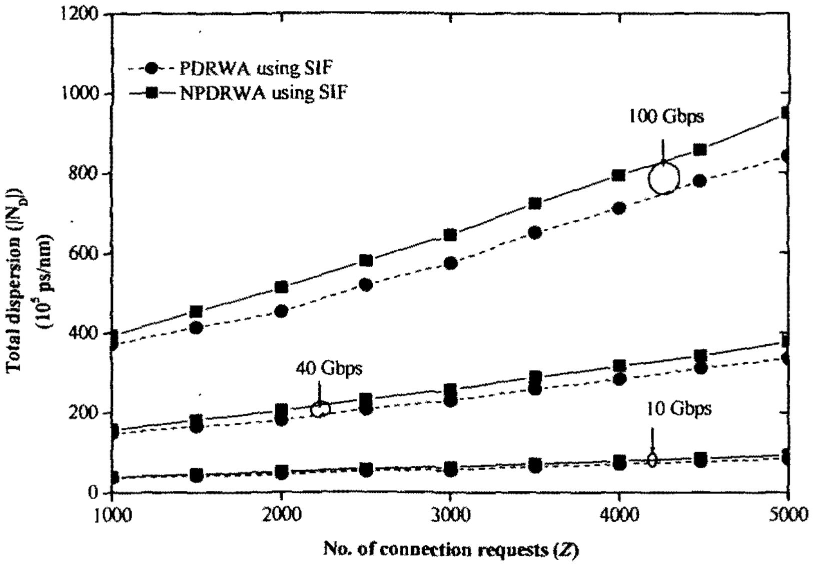


Figure 5-8: $|N_D|$ versus Z, obtained by using PDRWA and NDRWA in the Indian network with different channel speeds

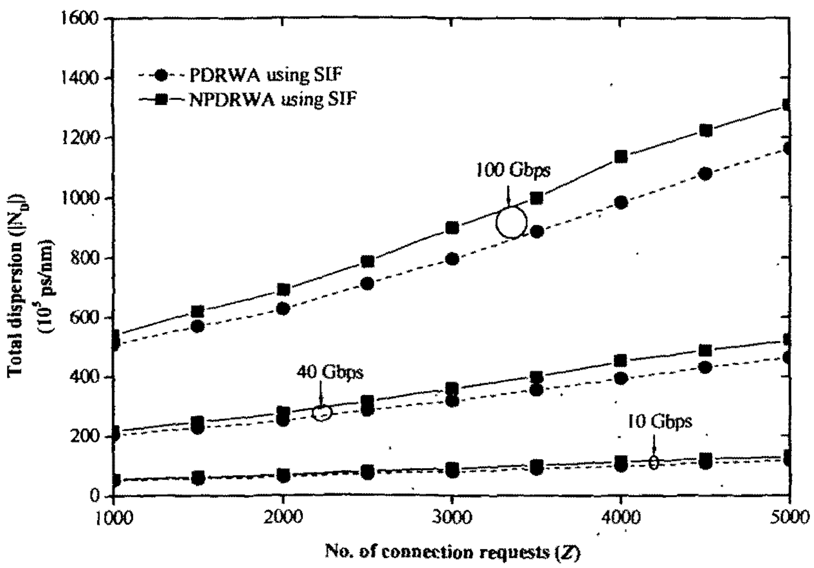


Figure 5-9: $|N_D|$ versus Z, obtained by using PDRWA and NDRWA in NSFNET with different channel speeds

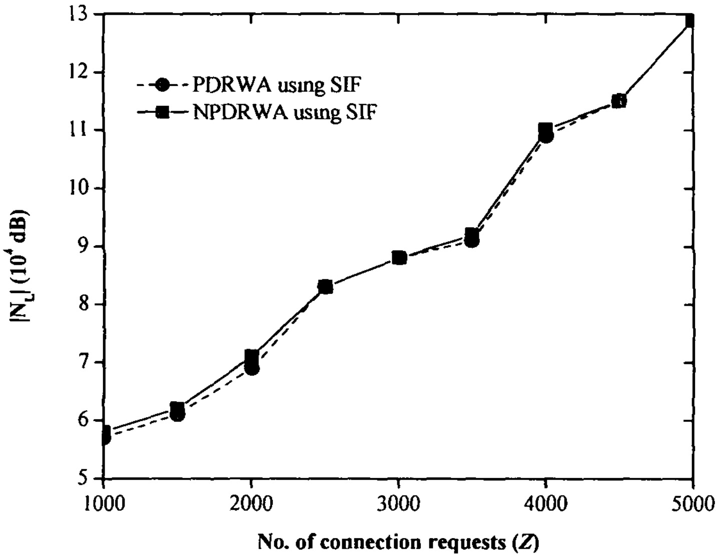


Figure 5-10: $|N_L|$ versus Z, obtained by using PDRWA and NDRWA in the Indian network with 10 Gbps channel speed

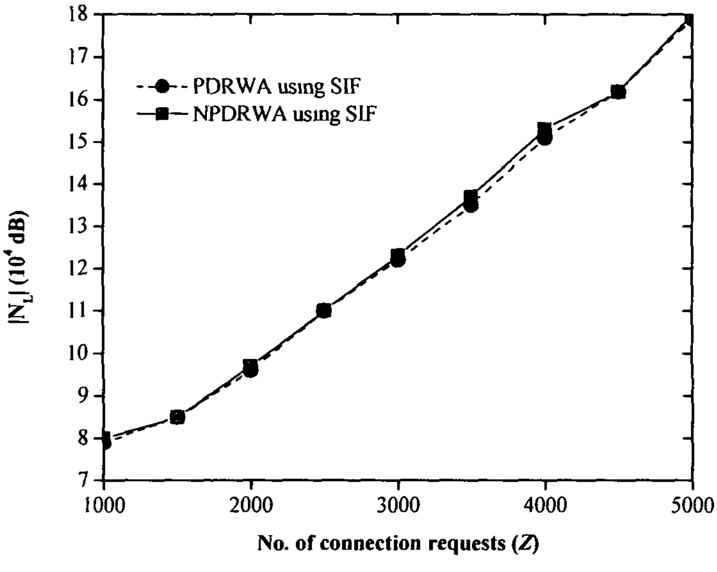


Figure 5-11: $|N_L|$ versus Z, obtained by using PDRWA and NDRWA in NSFNET with 10 Gbps channel speed

Furthermore, it has been reported [91] in the literature that for higher bit rate channel (≥10 Gbps), the pulse-broadening effect caused by polarization mode dispersion (PMD) degrades the signal quality Therefore, we have studied PMD effect in the PDRWA scheme with the use of SIF and DCF. The PMD [51,91,95]

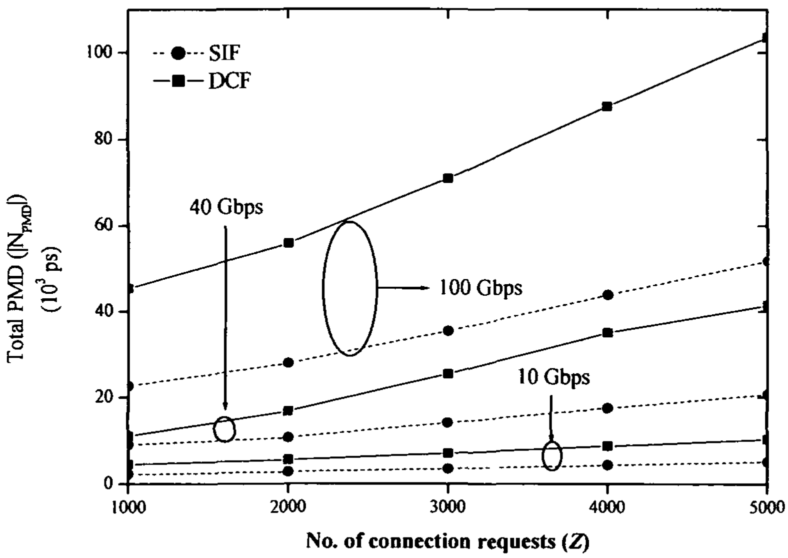


Figure 5-12: $|N_{PMD}|$ versus Z for SIF and DCF with different channel speeds (10, 40 and 100 Gbps) in the Indian network under non-blocking condition.

in a path with M hops can be estimated as given in Equation (5.10). The symbols used in this equation are given in Table 5.1.

$$PMD_{path} = B\sqrt{\sum_{j=1}^{M} D_{PMD}^{2} \cdot d_j} \tag{5.10}$$

Figure 5-12 shows the total PMD versus the number of connection requests, using SIF and DCF with different channel speeds, such as, 10, 40 and 100 Gbps in the Indian network. It is evident from the figure that as the number of connection requests increases, total PMD in the network increases irrespective of channel capacities. However, the total PMD using DCF is more than that of using SIF. This is because, the PMD coefficient of DCF is double than that of SIF [101]. It can be observed from Figure 5-12 that the PMD in the network increases with increase in channel speed. Furthermore, we found that the total PMD of NSFNET is greater than that in Indian network. This is mainly because of total lightpath distance in NSFNET is more than that in the Indian network.

5.5.2 Blocking Case

Here, we will show the performance of PDRWA scheme in terms of blocking probability already defined in chapter 3 (page number 45) under blocking condition of the network. The results are compared with NPDRWA for different numbers of wavelengths and connection requests.

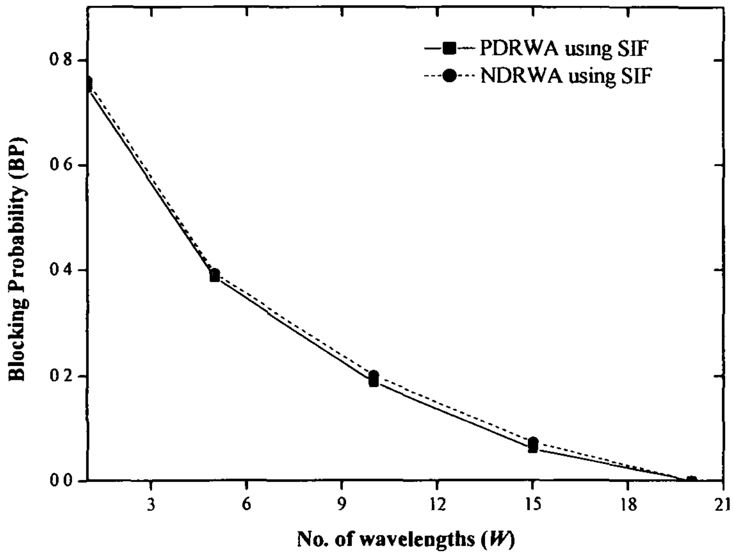


Figure 5-13: BP versus *W*, obtained by using PDRWA and NDRWA in the Indian network with 10 Gbps channel speed

Figure 5-13 and Figure 5-14 show the blocking probability versus total number of wavelengths, obtained by using PDRWA and NDRWA schemes in the Indian network and NSFNET, respectively, with 3000 number of connection requests and 10 Gbps channel speed. It is evident that the blocking probability decreases with increase in number of wavelengths for both the networks. However, the rate of decrease in blocking probability using PDRWA scheme is almost close to that of using NDRWA scheme. Furthermore, we have observed from Figure 5-13 and Figure 5-14 that the blocking probability in the Indian network is less compared to NSFNET.

Figure 5-15 and Figure 5-16 depict the total dispersion versus number of connection requests, obtained by using PDRWA and NDRWA schemes in the Indian network and NSFNET, respectively, under 5% and 15% blocking of connections. For comparison purpose we have incorporated the simulation result of total dispersion using NDRWA scheme with DCF under non-blocking condition in both the figures. It has been observed from Figurc 5-15 and Figure 5-16 that the

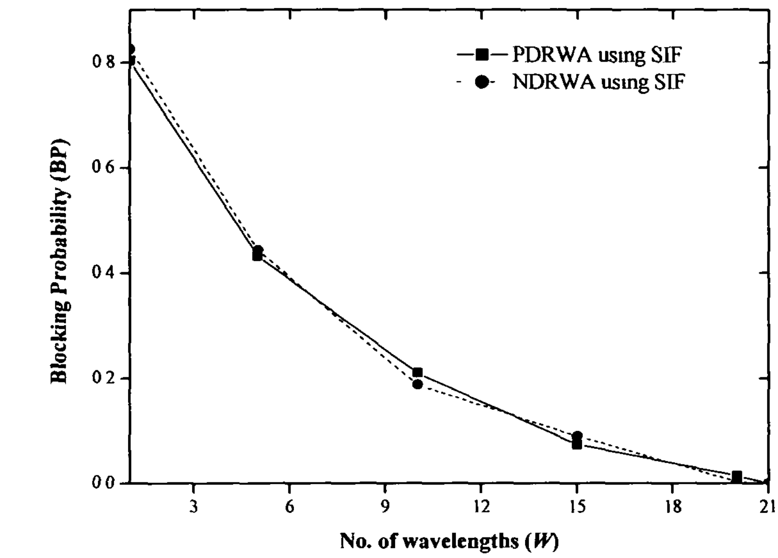


Figure 5-14: BP versus W, obtained by using PDRWA and NDRWA in NSFNET with 10 Gbps channel speed

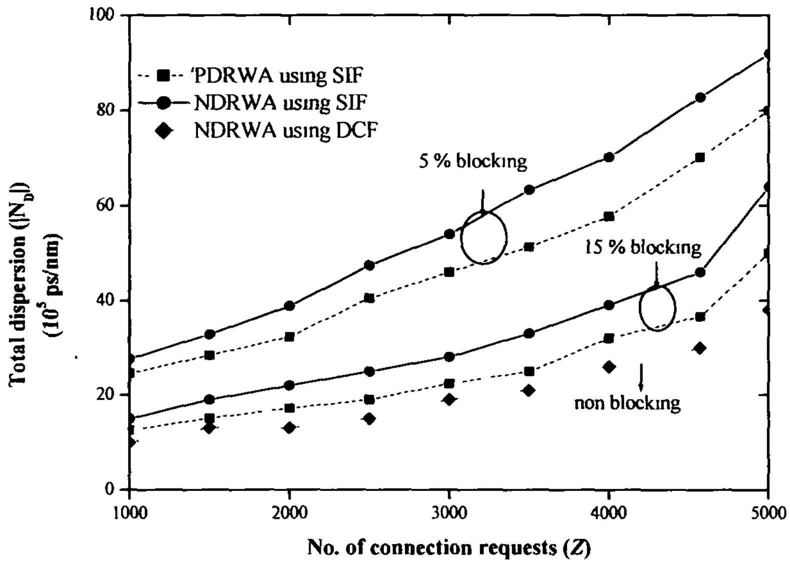


Figure 5-15: $|N_D|$ versus Z, obtained by using PDRWA and NDRWA in the Indian network under different blocking of connection requests

total dispersion using PDRWA scheme with 15% blocked connections is almost close to that of using NDRWA scheme with DCF.

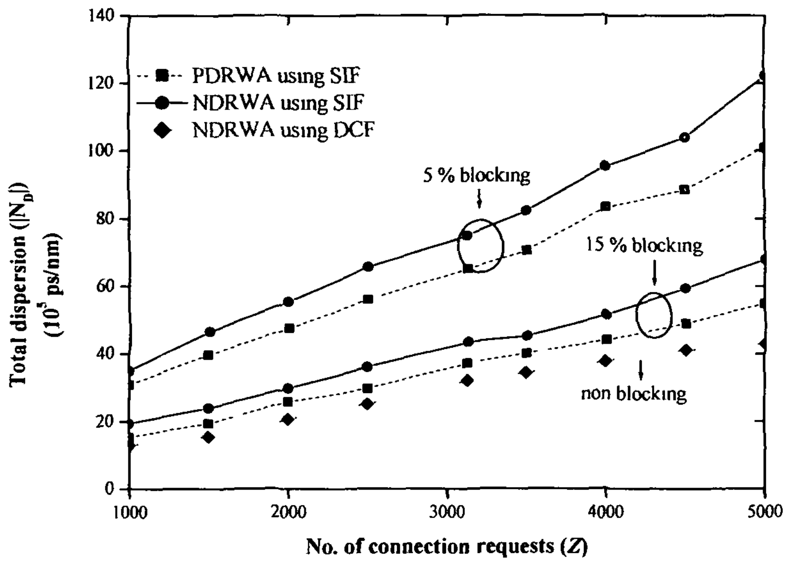


Figure 5-16: $|N_D|$ versus Z, obtained by using PDRWA and NDRWA in NSFNET under different blocking of connection requests

5.5.3 Q-factor Analysis

As dispersion in optical fiber degrades the quality of signal, it is also important to study the overall signal quality (Q-factor) in the network while applying the PDRWA scheme. The Q-factor of signal is given in Equations (5.11) and (5.12), respectively, for without PMD and with PMD cases as defined in [94,97,103]. The symbols used in the above equations are given in Table 5.1. Here, we will show the performance of PDRWA scheme in terms of overall signal quality (Q-factor) in the network. The results are compared with NPDRWA with the use of SIF and DCF for varying numbers connection requests and channel speeds.

$$Q_{withoutPMD} = \sqrt{\frac{OSNR}{EOP} \cdot \frac{\Delta f_{opt}}{\Delta f_{el}} \cdot EXTP} \tag{5.11}$$

$$Q_{withPMD} = \frac{Q_{withoutPMD}}{EOP_{PMD}} \tag{5.12}$$

where

$$EOP = 10log\left(\sqrt{1 + (D(\lambda) \cdot FL \cdot \frac{\sigma_\lambda}{\sigma_0})}\right) \tag{5.13}$$

$$EOP_{PMD} = 5.1\left(\frac{PMD_{path}}{T_B}\right)^2 \tag{5.14}$$

$$OSNR = P_{in} + 58 - P_s - NF - 10log_{10}N' \tag{5.15}$$

$$T_B = \frac{1}{B} \tag{5.16}$$

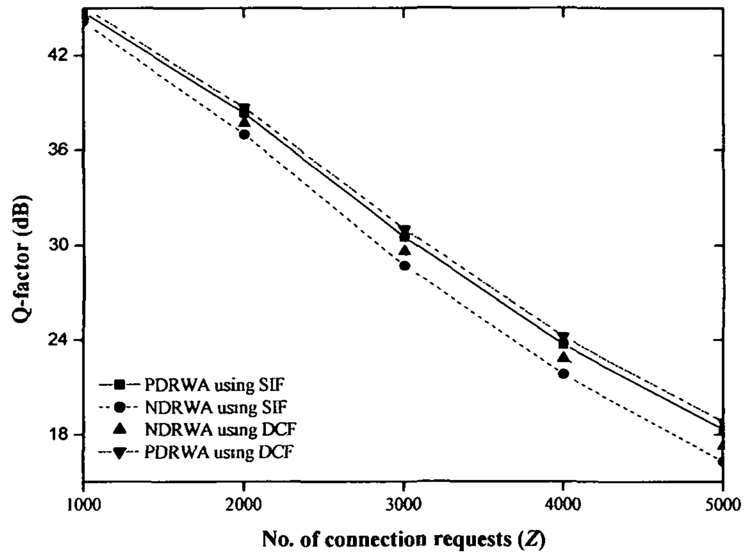


Figure 5-17: Q-factor versus Z, obtained by using PDRWA and NDRWA in the Indian network without PMD effect and 10 Gbps speed

Figure 5-17 and Figure 5-18 show the overall Q-factor versus number of connection requests, estimated by using PDRWA and NDRWA schemes in the Indian network and NSFNET, respectively. We have estimated Q-factor using both SIF and DCF while the channel speed is considered as 10 Gbps. In the figures, the Q-factors using different schemes have been estimated without incorporation of PMD effect. It is evident from Figure 5-17 and Figure 5-18 that the Q-factor of the signal decreases with increase in number of connection requests. This is due to increase of total lightpath distance with increase in connection requests. In the figures, Q-factor using NDRWA scheme with SIF is lower than that of using other schemes. The Q-factor using PDRWA scheme with SIF increases due to assignment of less dispersion wavelength to the connection requests having longer paths and vice versa. Furthermore, it can be observed from both Figure 5-17 and Figure 5-18 that Q-factor using PDRWA scheme with DCF is almost close to that of using PDRWA scheme with SIF. This is because, with the use of DCF more amplified spontaneous emission (ASE) noise is introduced in the network due to increase in number of EDFA to compensate enhanced propagation losses. It can be found from the figures that the Q-factor using PDRWA scheme with SIF is

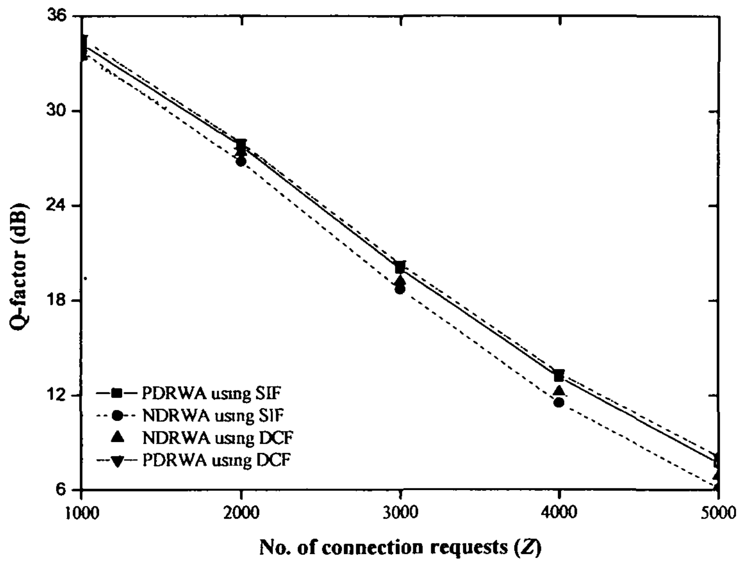


Figure 5-18: Q-factor versus Z, obtained by using PDRWA and NDRWA in NSFNET without PMD effect and 10 Gbps speed

more than that of using NDRWA scheme with DCF. We can also notice from Figure 5-17 and Figure 5-18 that the Q-factor in NSFNET is less than that in the Indian network.

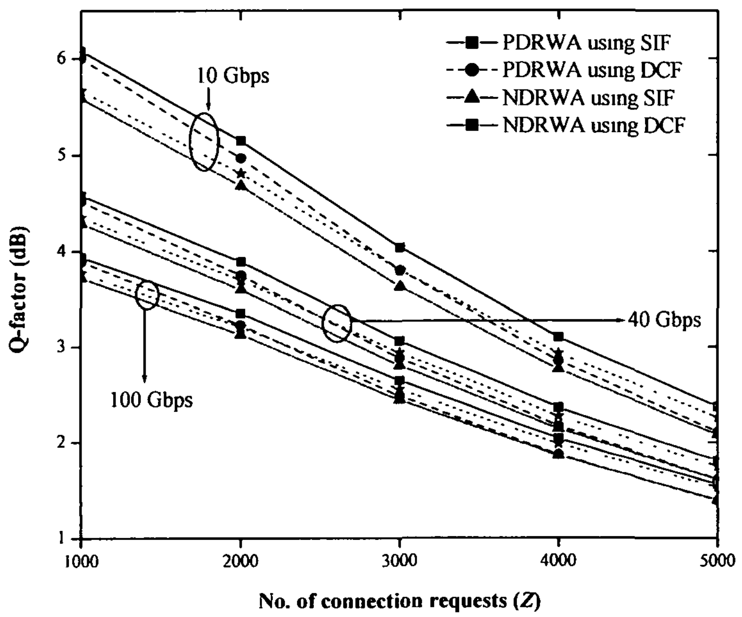


Figure 5-19: Q-factor versus Z, obtained by using PDRWA and NDRWA in the Indian network (without PMD effect and 10 Gbps speed).

Considering channel data speed greater than or equal 10 Gbps, we have studied the overall Q-factor in the network with incorporation of PMD effect. Figure 5-19 depicts overall Q-factor versus number of connection requests, estimated by using PDRWA and NDRWA schemes in the Indian network with use of SIF and DCF. In the figure, the Q-factors using different schemes have been estimated with incorporation of PMD effect. It is evident from the figure that the overall Q-factor decreases with increase in channel speed. This is mainly because dual imaging of bits at the receiver occurs due to pulse broadening of shorter bit signal. We have already observed in Figure 5-17 that the Q-factor (without PMD effect) of signal using PDRWA scheme with DCF is more than that of using other schemes. However, the overall Q-factor with PMD effect using PDRWA scheme with SIF is more than that of using PDRWA scheme with DCF. This is mainly due to higher PMD coefficient of DCF. Furthermore, it can be found from Figure 5-19 that in PDRWA scheme with SIF, the rate of decrease of Q-factor with number of connection request is less than that of other schemes due to lesser power penalty of SIF.

5.6 Conclusion

In this chapter, we have presented a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme to reduce the overall dispersion in optical networks. In this scheme, the connection requests having the same source-destination pair are groomed first to avoid intermediate O/E/O conversion and then these groomed connection requests are assigned wavelengths based on their lightpath distance, where connection requests with longer lightpath are assigned the wavelengths having lesser dispersion and vice versa. The effectiveness of the PDRWA scheme has been examined through its performance evaluation in two example optical networks, namely, (i) the Indian network and (ii) NSFNET. From the simulation study we draw the following conclusions:

- Although, the dispersion with use of DCF is lower than that of the SIF, the propagation loss in DCF is 3 times higher than that of SIF.
- It can be observed that the total dispersion in the network significantly reduces using PDRWA scheme with SIF, while maintaining the call blocking and without increasing total propagation loss in the network.
- We found that the total dispersion increases with channel speed but the rate of increase of total dispersion using PDRWA scheme is less than that of using NDRWA scheme.

- It has also been observed that Q-factor (with PMD effect) while using PDRWA scheme with SIF is more than that of using PDRWA scheme with DCF, due to the higher PMD coefficient.

Therefore, PDRWA scheme with SIF will lead to a cost-effective solution for high speed optical network design. Till now we have investigated the RWA problem with and without grooming for reducing the call blocking and improving the quality-of-service (QoS) in terms of signal quality in optical networks. Nowadays, survivability against failures has become an important issue in WDM based optical networks due to increasing dependency on this network, which will be addressed in the next chapter.

Chapter 6

QoS-aware Fault Resilience Wavelength Assignment Scheme

6.1 Introduction

Wavelength routing together with wavelength division multiplexing (WDM) is a promising technology for next generation high performance networks due to its many desirable properties like - higher bandwidth availability, low bit error rate, low power requirements and low cost. WDM technology provides enormous bandwidth in optical fiber by allowing simultaneous transmission of traffic on many non-overlapping channels (or wavelengths). Recently, traffic grooming [10, 54–56, 56–61] mechanism has been incorporated with WDM technology to further enhance the channel utilization. As a result, a single fiber can nowadays carry a huge amount of information which is in the order of Tbps range. Therefore, failure of a network component, such as optical fiber and network node, can disrupt communications for millions of users which can lead to a greater loss of data and revenue. As an example, in the year 2004, the Gartner Research Group had lost approximately 500 million dollars due to failure of optical network [104]. Thus, the survivability [21, 22, 105] against the failures have become an important requirement in an optical network.

In this direction, researchers have demonstrated that protection [8, 10, 70, 106–108] and restoration [8, 10, 22, 70, 107, 109] are the key strategies for handling failures in optical networks and hence to improve the network reliability. It had been revealed that the recovery time of protection technique is much smaller than that of restoration scheme. This is because in protection technique, backup paths are computed prior to fault occurrence. On the other hand, restoration scheme computes the backup paths dynamically after the fault occurrence. Therefore, protection technique is more preferable for designing a faster recovery system. Till date, mainly two types of protection mechanism, namely, (i) shared protection (1:M) [10, 108, 110] and (ii) dedicated protection (1:1) [10, 70] have been used by the researchers. In a shared protection, a protection/ backup path is shared among all the working paths, whereas in a dedicated protection, a dedicated protection/ backup path is reserved for each working path. However, all the approaches mentioned above have more or less some limitations as follows - In dedicated protection, a huge number of wavelength channels are reserved in advance irrespective of the occurrence of a fault, and shared protection scheme is unable to provide the network reliability in a situation when simultaneous faults occur along the working paths. To the best of our knowledge, no quality of service (QoS)-aware fault resilience routing and wavelength assignment scheme with incorporation of traffic grooming mechanism has been reported in the literature. We address this issue to improve the reliability in the network while maintaining a better quality of signal and better utilization of network resources.

In this chapter, we have proposed a QoS-aware fault resilience wavelength assignment (QFRWA) scheme with incorporation of traffic grooming mechanism to improve the reliability of the network while maintaining the signal quality and better utilization of network resources. The performance analysis of the QFRWA scheme has been conducted to evaluate the suitability of the scheme in terms of reliability and overall signal quality in the network. The results have been compared with a similar type of non QoS-aware fault resilience wavelength assignment (NQFRWA) scheme. The rest of this chapter is organized as follows. Section 6.2 formally defines the problem we address and formulates the objective function. In that section, we also address the model assumptions, and define symbols and notations which are used throughout this chapter. The fault detection network architecture is presented in section 6.3 along with the functionality of it's components. Section 6.4 presents the QFRWA scheme with incorporation of traffic grooming mechanism. Further in that section, we elaborate the working principle of QFRWA scheme with the help of some examples. Section 6.5 evaluates the performance of the proposed scheme under blocking and non-blocking conditions. Finally, section 6.6 concludes this chapter.

6.2 Problem Statement

We model the physical topology of an optical network as a connected graph G' (V', E'), where V' and E' are the set of nodes and set of bi-directional optical fiber links in the network, respectively. Here, each link $e \epsilon E'$ has a finite number of wavelengths denoted by W. A non-negative link cost $C(e)$ is assigned to every link e in the network, which represents the distance between the adjacent node pair connected by e. The following assumptions are considered in our model.

6.2.1 Assumptions

- Each fiber link can carry an equal number of wavelengths and the network is without wavelength conversion capabilities.
- All the lightpaths sharing at least one fiber link are allocated distinct wavelengths.
- Each node can work as both an access node and a routing node.
- Each node is equipped with a fixed number of tunable transceivers.
- Each node is capable of multiplexing/demultiplexing as many connection requests having the same source-destination pair as possible within the channel capacity.
- Each optical amplifier and network node has a fault surveillance controller.
- The dedicated wavelength, λ_0 is being used as a supervisory channel. It is normally spaced apart from the other wavelengths to carry control signals between all adjacent pairs of controllers intended for network management.
- All the channels have the same bandwidth.

6.2.2 Notations and Symbols

For the remainder of this chapter, the symbols and notations used are summarized in Table 6.1.

Table 6.1: Used notations and symbols

Notations / Symbols	Comments
N	Total number of nodes in the network
E	Total number of links in the network
Z	Total number of connection requests in the network
Y	Total number of groomed connection requests in the network
K	Total number of lightpaths for a connection request
$D(\lambda)$	Coefficient of total dispersion in $ps/(nm.km)$ of a wavelength
Δf_{opt}	Optical bandwidth
Δf_{el}	Electrical bandwidth
P_s	Total span loss
NF	Erbium doped fiber amplifier (EDFA) noise factor. It mainly represents amplified spontaneous emission (ASE) noise
EXTP	Extinction ratio penalty
P_{in}	Amplifier input power
N'	Total number of spans
d_k	Fiber length of the k^{th} hop in kilometer, which is an integer value
FL	Fiber length in kilometer
σ_λ	Spectral width
σ_0	Pulse width
$\sum_{k=1}^{M} D_{PMD}^2 \cdot d_k$	Total PMD in a path with M hops
$N_R(t)$	Average reliability in the network
N_Q	Overall signal quality (Q-factor) in the network
Q_j	Q-factor of a connection, j
$R_i(t)$	Reliability of component, i for a time period, t
$B(r_i^{s_i,d_i})$	Bandwidth requirement of a connection request
B	Channel bit rate
$R_{s,d}^{RSP}(t)$	Reliability of a connection using RSP technique
$R_{s,d}^{SP}(t)$	Reliability of a connection using SP technique
R_1	Reliability of each primary path
R_2	Reliability of each backup path
$R_i(t)$	Reliability of component, i for a time period, t

$N_R^{RSP}(t)$	Average reliability in the network using RSP technique
$N_R^{SP}(t)$	Average reliability in the network using SP technique
f_p	Failure rate of each primary path
f_s	Failure rate of each backup path
V''	Set of virtual links in the network
E''	Set of directed virtual links in the network
G''	Virtual topology of physical topology

6.2.3 Objective Function

As recovery performance of an optical network is determined by the reliability function, we have formulated the average reliability in the network using the reliability function of component, i over a period of time, t. It has already been shown in chapter 5 that as the signal propagates through optical fiber, the overall signal quality degrades with distance traveled. Therefore, our objectives of incorporating a fault resilience technique with PDRWA are two-fold as follows.

- To maximize $N_R(t)$, the average reliability in the network
- To maximize N_Q, the overall signal quality (Q-factor) in the network by reducing total dispersion in the network without using any dispersion compensating device like - dispersion compensating fiber (DCF)

Where $N_R(t)$ and N_Q are defined in Equations (6.1) and (6.2), respectively.

$$N_R(t) = \frac{\sum_{j=1}^{Z} (1 - \prod_{i=1}^{n}[1 - R_i(t)])}{Z} \tag{6.1}$$

$$N_Q = \sum_{j=1}^{Z} Q_j \tag{6.2}$$

$$Q = \frac{\sqrt{\frac{P_{in}+58-P_s-NF-10log_{10}N'}{10log\left(\sqrt{1+(D(\lambda)\cdot FL\cdot\frac{\sigma_\Delta}{\sigma_0})}\right)} \cdot \frac{\Delta f_{opt}}{\Delta f_{el}} \cdot EXTP}}{5.1\left(B^2\sqrt{\sum_{k=1}^{M} D_{PMD}^2 \cdot d_k}\right)^2} \tag{6.3}$$

Using Equations (6.1) and (6.2), the average reliability and overall Q-factor in the network are computed for the given set of connection requests. In Equation 6.3,

$D(\lambda)$ represents the coefficient of total dispersion in *ps/(nm.km)* of a wavelength whose estimation has been shown in chapter 5 using Equations (5.2)-(5.9).

6.3 Fault Detection Network Architecture

A network is being designed in such a way that if any link or node failure occurs in the network during transmission, the following strategies are adopted [105, 109] to identify fault.

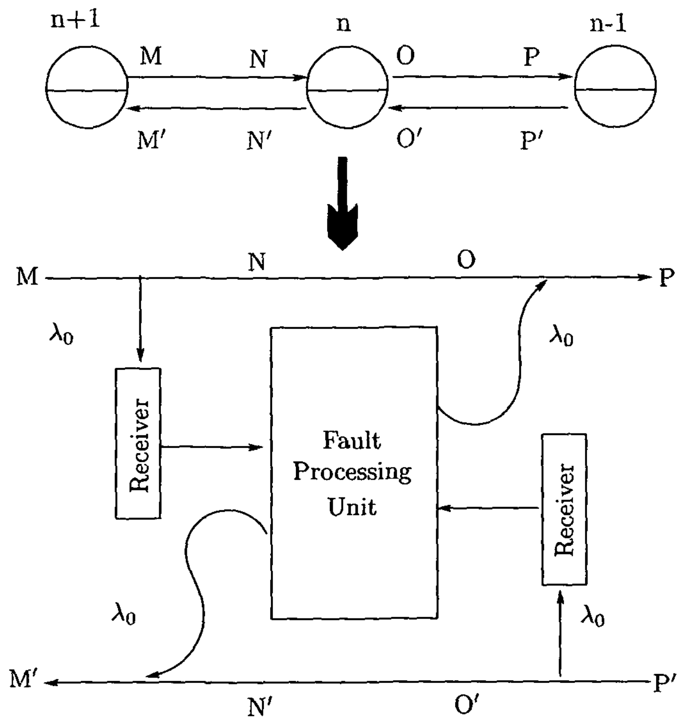


Figure 6-1: Fault detection for link segments and optical amplifiers

6.3.1 Link and Amplifier Fault Detection

Figure 6-1 shows the fault monitoring and isolation mechanism for each pair of optical amplifiers. The control signal at the supervisory channel, λ_0 is monitored continuously to determine whether a fault occurs or not by using the presence or absence of light. In this figure, 'n' is an amplifier stage while 'n+1' and 'n-1' could be an end node or another amplifier stage. Under normal operation (presence of light/ active state), the control signal at wavelength, λ_0 is simply passes through fault processing unit. Otherwise, the operation of the two segments, namely, MN

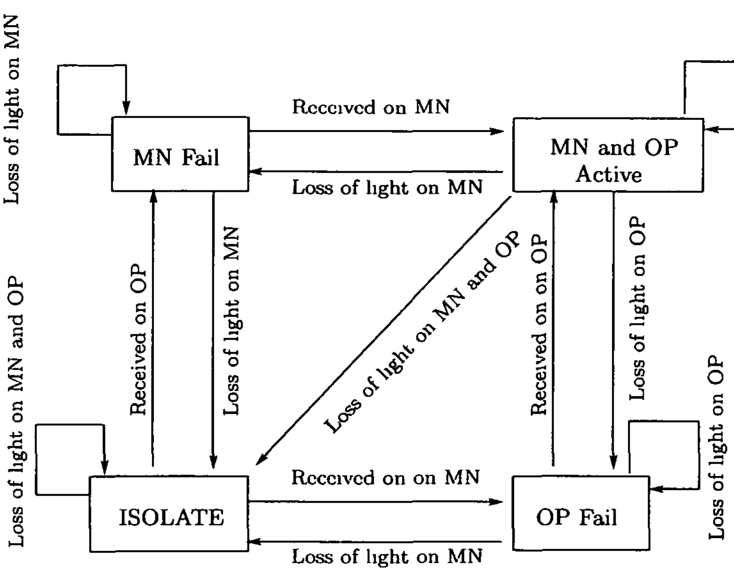


Figure 6-2: Link and amplifier fault detection using finite-state machine

and OP is controlled by a state machine belongs to the fault processing unit as shown in Figure 6-2. If a loss of light condition is detected on one of the links, say, on MN optical segment link, the fault processing unit enters into the MN Fail state. Then this unit generates a new signal indicating presence of a fault and sends it on the link OP. This enables the controller in the neighbor node P to determine the location and type of the failure. If a loss of light condition is detected on both the MN and OP link simultaneously, the fault processing unit enters into the isolate state. Then, this fault processing unit generates a new control signal indicating a fault and sends it on both the MN and OP links. This enables the controllers of both the neighbor nodes M and P to determine the location and type of the failure.

6.3.2 Node Fault Detection

Detecting a fault inside a network node is more difficult. Figure 6-3 shows the logical fault detection architecture of a network node which uses a number of devices, these are (i) F number of wavelength division multiplexers (WDMs) /wavelength division demultiplexers (WDDMs), (ii) W number of thermo-optic switches (TOSWs), (iii) W number of transmitters (TXs), (iv) W number of receivers (RXs), (v) W number of add-drop multiplexers (ADMs), (vi) a wavelength router based on the priority-based dispersion-reduced wavelength assignment (PDRWA) algorithm already discussed in Algorithm 3 (page number 86) and QFRWA scheme, (vii) a SONET STS multiplexer / SONET STS demultiplexer, and (vii) a fault

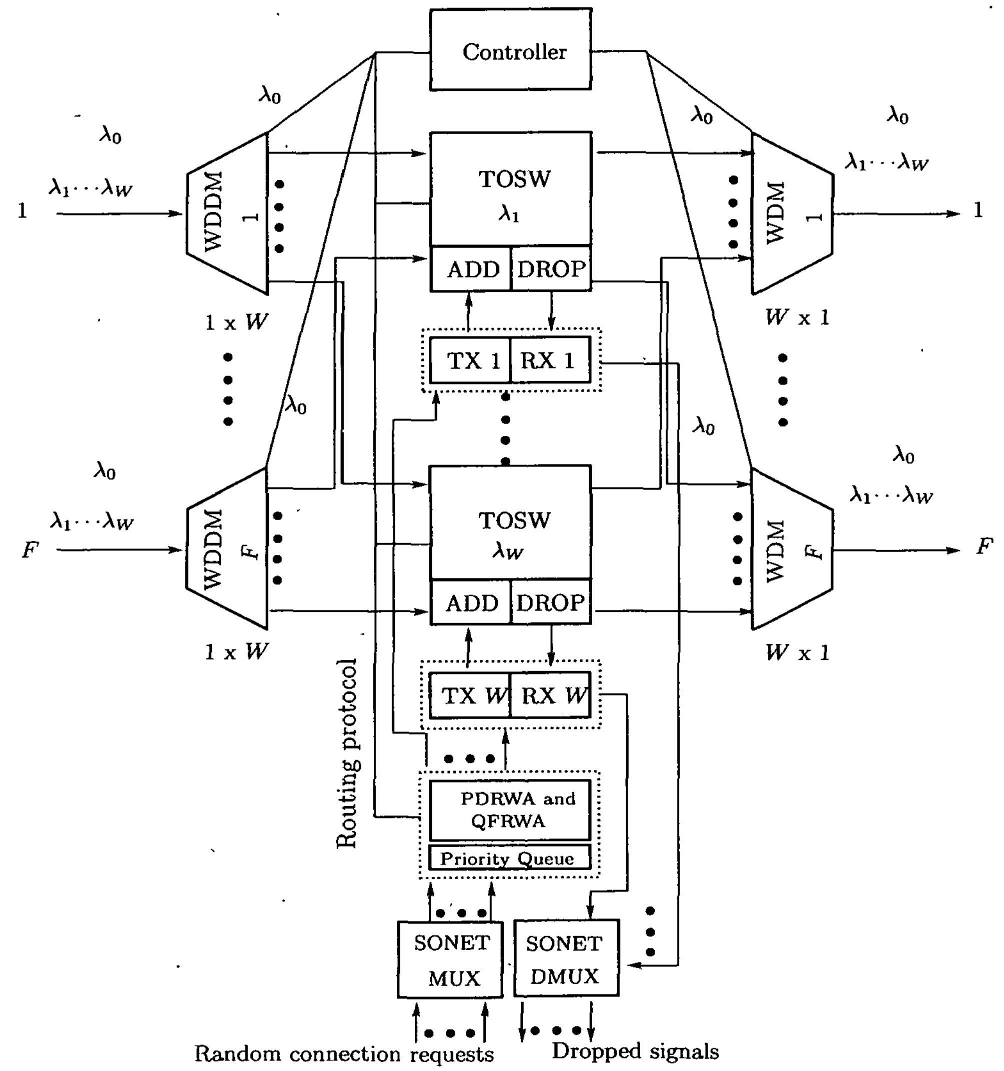


Figure 6-3: Fault detection node architecture

controller. If a component of the node fails, at least one of the lightpaths flowing through the devices will be affected. This will result in a loss of light condition being detected at the ends of the lightpaths. Then the end nodes will communicate with each node along the lightpath to determine whether it is a link / amplifier failure or a node failure. The failure of a component of a node can be determined by the fault controller through injecting and monitoring a test signal for each of the components along the route of the lightpath which has failed. After detecting a fault, the fault controller of the node in which a fault occurs, sends the fault information to the controllers of the neighbor nodes. In this way with the help of a fault controller, occurrence of a fault can be detected.

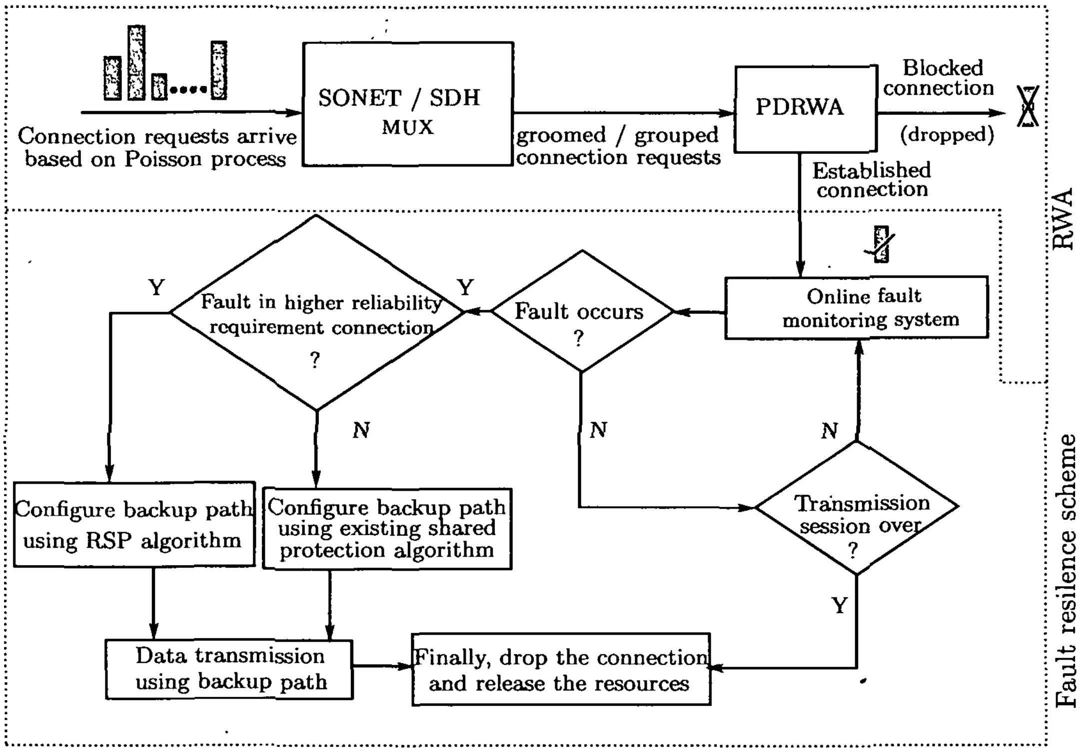


Figure 6-4: Framework of the QFRWA scheme

6.4 QoS-aware Fault Resilience Wavelength Assignment

We have developed QoS-aware fault resilience wavelength assignment (QFRWA) scheme which is intended to improve the average reliability in the network while maintaining a better signal quality and better utilization of network resources. There are mainly two steps involved in constructing the complete framework of QFRWA, namely, (i) grooming of connection requests and RWA approach and (ii) fault management. The overall framework of the scheme is being depicted in Figure 6-4. Initially, a number of connection requests arrive at the system randomly based on any distribution. At first, the connection requests having the same source-destination pair are groomed/grouped with the SONET STS multiplexer. Then these groomed connection requests are served for lightpath establishment as per PDRWA algorithm. Finally, the established groomed connections with higher reliability requirement are protected to increase the network reliability using the Algorithm 4 discussed in section 6.4.2. The ordinary connections, that is connections without extra reliability requirement are protected by the shared protection (SP) technique for better utilization of the network resources. The details of the two steps are presented in the following subsections.

6.4.1 Grooming of Connection Requests and RWA Approach

The aim of connection requests grooming is to enhance the effective utilization of a given capacity optical network. In this part, the connection requests are groomed by following a similar traffic grooming strategy as discussed in section 4.4 of chapter 4. Then these groomed connection requests are served for lightpath establishment in accordance with the PDRWA scheme already discussed in chapter 5. Using the PDRWA scheme, longer lightpath groomed connections are always given higher priority compared to groomed connections having shorter lightpath distance. Here, our goal is to reduce the total dispersion in the network without using dispersion compensating device, like - DCF and hence to improve the overall quality (Q-factor) of the signal in the network, without substantial increase in network setup cost. In PDRWA scheme, K+1 number of paths (including the primary path) are computed for the connection requests on the basis of link-state information. Among K+1 number of paths, first K paths are used for lightpath establishment and $K+1^{th}$ paths can be used as backup path. The backup path is assured to be link disjoint to the working path of each connection.

6.4.2 Fault Management

This section presents the fault management of the QFRWA scheme. In this part, the established connections with higher reliability requirement are protected using reliable shared protection tree(s) which is/are constructed using Algorithm 4. This protection tree is constructed by restricted sharing of backup paths in the sub branches of the breadth-first protection tree (BFPT). However, other backup paths must be shared among themselves. The ordinary connections, that is connections without extra reliability requirement, are protected by shared protection tree(s) which is/are constructed using shared protection technique. Our goal in here is to improve the reliability in the network while maintaining better utilization of network resources. To achieve this goal, the established connections with higher reliability requirement are protected using reliable shared protection tree(s) by restricted sharing of the backup paths in the sub branches of the BFPT. Use of dedicated protection for connections may lead to a situation, where a huge number of wavelength channels is reserved in advance irrespective of the occurrence of a fault. On the other hand, shared protection scheme is unable to provide the network reliability in a situation when simultaneous faults occur along the working paths. Therefore, fault management part of the QFRWA scheme is able to increase the reliability for the higher reliability requirement connections. At the same time, this scheme also fairly manages the reliability of ordinary connections using the shared protection technique, while maintaining better utilization of network resources compared to dedicated protection technique.

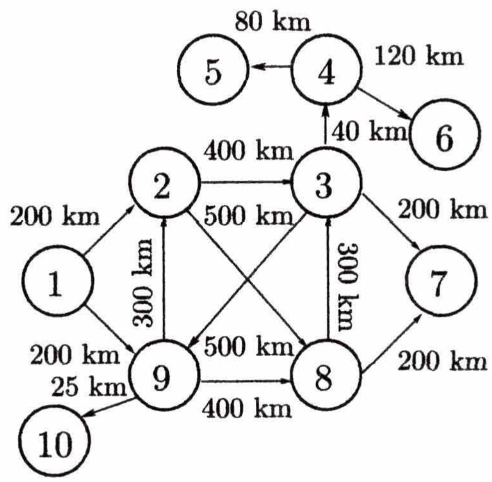


Figure 6-5: Physical topology of sample example network

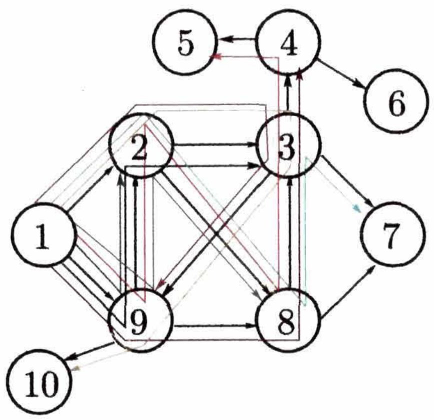


Figure 6-6: Virtual topology (G'') of sample example network using K+1th paths of established groomed connections

For better understanding of the functionality of Algorithm 4, we explain it with the help of a sample example network as shown in Figure 6-5. The sample network consists of 9 nodes with 13 directed optical links. We assume 9 established higher reliability requirement groomed connections given by, $C = \{c_1^{1,2}, c_2^{1,3}, c_3^{1,4}, c_4^{1,5}, c_5^{1,6}, c_6^{1,7}, c_7^{1,8}, c_8^{1,9}, c_9^{1,10}\}$ and their K+1th paths are 1-9-2, 1-9-2-3, 1-9-8-3-4, 1-9-2-8-3-4-5, 1-9-2-8-3-4-6, 1-2-8-3-7, 1-9-2-8, 1-2-3-9-10, respectively. Using these K+1th paths, the virtual topology G$''$ is formed as shown in Figure 6-5. From this virtual topology, we construct a breadth-first protection tree (BFPT) as shown in Figure 6-7(a). This BFPT is taken as the input in Algorithm 4 to construct a reliable protection tree as depicted in Figure 6-7(b). As shown in the figure, we have restricted the sharing of backup paths in sub branches of the protection tree. Therefore, the backup paths 1-2-8, 1-2-3-4-5, 1-2-3-4-6 and 1-2-3-7 could not be shared by themselves and they are assigned with different wavelengths λ_1, λ_2, λ_3 and λ_4, respectively. The details of the establishment of reliable shared protection

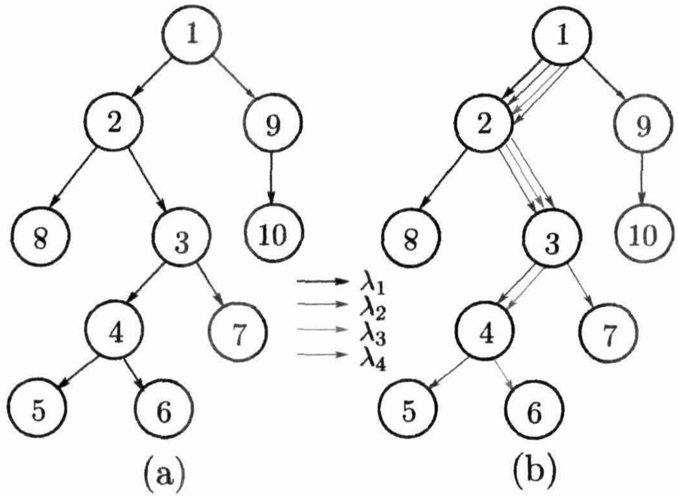


Figure 6-7: (a) Breadth-first protection tree (BFPT) and (b) reliable protection tree

tree(s) are given in the Algorithm 4. The overall time complexity of this algorithm can be expressed as $\equiv O(N + E)$.

The recovery performance of an optical network is expressed by a reliability function. Reliability of an optical network is defined as the probability of failure free operation of the network over a period of time. We use the reliability model of both shared protection (SP) and reliable shared protection (RSP) techniques. The reliability function of component, i over a period of time, say t, can be expressed as given in Equation (6.4) [111].

$$R(t) = 1 - \prod_{i=1}^{n}[1 - R_i(t)] \tag{6.4}$$

In our fault model, R_1 (*i.e.* $0 \leq R_1 \leq 1$) and R_2 (*i.e.* $0 \leq R_2 \leq 1$) represent the reliability of each primary path (PP) and backup path (BUP), respectively. To compare the reliability that can be achieved between node-1 to node-2 using SP and RSP techniques, we consider the reliability block diagram (RBD) as shown in Figure 6-8. In this figure, SP technique contains one backup path, whereas the RSP technique contains four backup paths due to restricted sharing of backup

Algorithm 4: Establishment of reliable protection trees (ERPT)

```
Input: Breadth-first protection tree (BFPT), T(V'', E'') constructed from the
       virtual topology, G'' (output of PDRWA algorithm already explained in
       page number 86). Here V'' and E'' are the set of virtual nodes and
       directed virtual links, respectively, in the network
Output: Reliable protection tree(s)
begin
    Mark all nodes of the tree T as 'unvisited'
    Let r be the root of the tree T, mark r as 'visited'
    for ∀ u ∈ Neigh_r do
        /* Neigh_r : Set of neighbors of r                              */
        Check for available wavelength λ_i, in the link r-u (where i=1, 2,···, W)
        if (available λ_i) then
            Reserve λ_i as a protection path
        else
            No protection path formed
        Enqueue u into the queue, Q
        Mark u as 'visited'
    while (Q not empty) do
        u=Dequeue (Q)
        for ∀ x ∈ Neigh_u do
            if (x=first neighbor or the only neighbor) then
                Check for available wavelength λ_i, in the link x-u
                if (available λ_i) then
                    Reserve λ_i in the end-to-end r-x link as a protection path
                    according to wavelength continuity constraint
                else
                    No protection path formed
            else
                Check for available wavelength λ_j, in the link x-u (where j=1,
                2,···, W)
                if (available λ_j) then
                    Reserve λ_j (j > i) in the end-to-end link r-x as a protection
                    path according to wavelength continuity constraint
                else
                    No protection path formed
            Mark x as 'visited'
            Enqueue x into the queue, Q
```

paths in sub branches of the BFPT as shown in Figure 6-7(a). The reliability using the SP technique of a connection between source, s to destination, d over a period of time, t can be estimated as given in Equation (6.5).

$$R_{s,d}^{SP}(t) = 1 - [1 - R_1(t)] \cdot [1 - R_2(t)] \tag{6.5}$$

The average reliability in the network using the SP technique for all connections

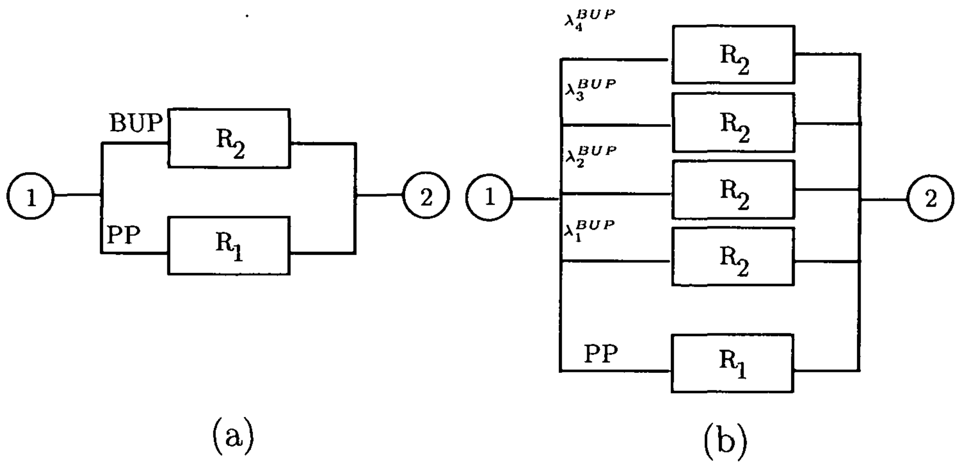


Figure 6-8: Reliability block diagram using (a) SP and (b) RSP techniques from node-1 to node-2

over a period of time, t can be estimated as given in Equation (6.6).

$$N_R^{SP}(t) = \frac{\sum_{j=1}^{Z} R_{s,d}^{SP}}{Z} \tag{6.6}$$

Similarly, the reliability of a connection between source, s to destination, d using the RSP technique over a period of time, t can be estimated as given in Equation (6.7).

$$R_{s,d}^{RSP}(t) = 1 - [1 - R_1(t)] \cdot [1 - R_2(t)]^n \tag{6.7}$$

The average reliability in the network using the RSP technique for all connections over a period of time, t can be estimated as given in Equation (6.8).

$$N_R^{RSP}(t) = \frac{\sum_{j=1}^{Z} R_{s,d}^{RSP}}{Z} \tag{6.8}$$

As,

$$R_{s,d}^{RSP}(t) \geq R_{s,d}^{SP}(t) \tag{6.9}$$

Therefore,

$$N_R^{RSP}(t) \geq N_R^{SP}(t) \tag{6.10}$$

From the above Equations (6.5)-(6.10), it is clear that RSP technique can provide more reliability compared to the existing SP technique with the use of some extra resources.

6.5 Performance analysis

In this section we will present simulation results in two experimental setups to show that QFRWA improves reliability while maintaining better utilization of network resources and a better quality of signal. Our experimental setup consists of 14 nodes with 24 bi-directional physical links of the Indian network and 14 nodes with 21 bi-directional physical links of NSFNET [10] as shown in Figure 3-1 (page number 44) and Figure 3-2 (page number 45), respectively. The following assumptions have been made for the purpose of simulations.

- The distances between adjacent cities are taken as given in Figure 3-1 and Figure 3-2 for configuring the example networks - the Indian network and NSFNET, respectively.
- Measurements can be performed on materials contemplated for core GeO_2:86.5 SiO_2 compositions and for claddings Quenched SiO_2, respectively, [92] as shown in Table 5.2 (page number 89).
- Wavelength range considered is from 1.520 μm to 1.590 μm due to its lower propagation loss.
- The spacing between two wavelengths is taken as 0.8 nm for 100 GH_z frequency spacing according to ITU G.694.1 [93].
- The connection requests are generated randomly based on a Poisson process, and the arrival time between two successive requests follows an exponential distribution. We choose the Poisson model because the burstiness of traffic on the backbone is usually suppressed by the huge amount of aggregation of services and the actual traffic distribution remains unknown.
- Among generated connection requests, higher reliability requirement connection requests and ordinary connection requests (without extra reliability requirement) are considered with an equal probability.
- The holding times of the connection requests are exponentially distributed. For the sake of simplicity, the holding time of all the connection requests having same source-destination pair are assumed to be same. However, differences in holding times for connection requests having same source-destination pair can be handled by taking the maximum of their holding times (similar to [52]) as the holding time for all of them.

- The maximum bandwidth requirement of a connection is 622.08 Mbps according to SONET OC-12/STS-12 [9].
- As the quality of the signal (Q-factor) varies with channel speed, we consider wavelength channels having three different capacities [9], such as, 10 Gbps (OC-192/STS-192), 40 Gbps (OC-768/STS-768) and 100 Gbps, respectively. For these capacities, each wavelength channel can respectively accommodate a maximum 16, 64 and 160 number of connection requests belonging to the same source-destination pair.
- For reliability measurement, we consider the failure rates of each primary path, denoted by f_p, and backup path, denoted by, f_s, as .01/hour and .005/hour,respectively. This failure rates are generally considered for electronic communication systems [112]. We also considered the time duration is 24 hours.
- The used system parameters are already summarized in Table 5.3 (page number 89).

We have performed the simulation study of the QoS-aware fault resilience wavelength assignment (QFRWA) scheme with number of connection requests varying from 1000 to 5000, distributed randomly among all the possible source-destination pairs. We have compared the results with a similar type of NQFRWA scheme, where First-fit (FF) [10] method has been implemented for the wavelength assignment.

6.5.1 Blocking case

Here, we will show the performance of QFRWA scheme in terms of blocking probability under blocking condition of the network. The situation where some connection requests are blocked or rejected due to unavailability of a required wavelength on the end-to-end path is defined as the blocking condition. The results are compared with three different schemes, namely, (i) NQFRWA with incorporation of dedicated protection, (ii) NQFRWA with incorporation shared protection and (iii) NQFRWA without protection.

We have already observed from Figure 4-5 (page number 66) that the variation of blocking probability with number of wavelengths, using up to three (*i.e.* K=4) alternate paths is close to that of using up to two (*i.e.* K=3) alternate paths in the Indian network. Similarly, in NSFNET (Figure 4-6 of page number

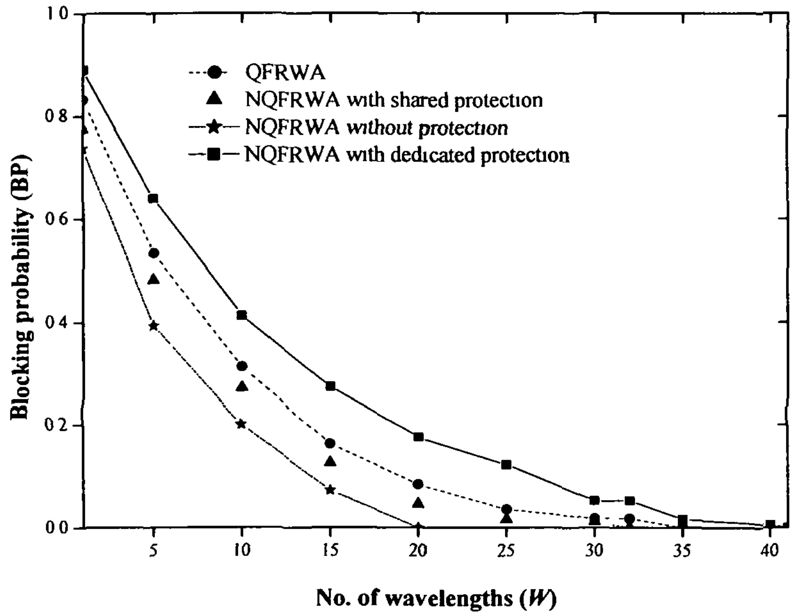


Figure 6-9: BP versus *W*, obtained by using QFRWA and NQFRWA (without protection, with incorporation of dedicated and shared protections) schemes in the Indian network

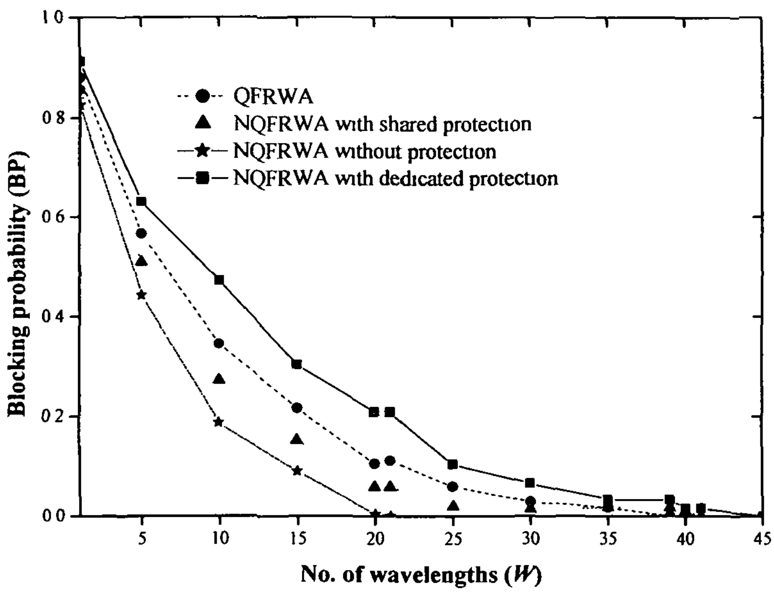


Figure 6-10: BP versus *W*, obtained by using QFRWA and NQFRWA (without protection, with incorporation of dedicated and shared protections) schemes in NSFNET

66), the variation of blocking probability using up to two (*i.e.* K=3) alternate paths is close to that of using up to one (*i.e.* K=2) alternate path. Our other observation from Figure 3-5 (page number 47) and Figure 3-6 (page number 48) is that the average setup time increases with increase in number of paths. Therefore, for RWA purpose of both QFRWA and NQFRWA schemes, we have considered the number of alternate paths up to one and two in NSFNET and the Indian network, respectively. The second and third alternate paths of each connection are reserved as backup paths in NSFNET and the Indian network, respectively. The difference of number of alternate paths in NSFNET and the Indian network is mainly due to the presence of lower number of optical physical links in NSFNET compared to the Indian network.

Figure 6-9 and Figure 6-10 show the blocking probability versus the number of wavelengths, obtained by using QFRWA and NQFRWA schemes in the Indian network and NSFNET, respectively, with 3000 connection requests. For comparison purpose, we have incorporated dedicated and shared protections with the NQFRWA scheme. In incorporating of dedicated and shared protections with NQFRWA scheme, we have considered the same reliability requirement for all these 3000 connection requests. If the probability of reliability requirement for connection requests (either higher reliability requirement connection requests or ordinary requests) varies, the performance of the NQFRWA scheme with dedicated and shared protection techniques remains almost same. Therefore, we do not consider the user reliability requirement during the incorporation of dedicated and shared protection techniques. From Figure 6-9 and Figure 6-10, we can observe that the blocking probability decreases with increase in number of wavelengths. However, the blocking probability using NQFRWA scheme with dedicated protection is more than that of using other schemes. This is because dedicated wavelength channels are reserved for connections in advance irrespective of the occurrence of a fault. We have found that the blocking probability using the QFRWA scheme is slightly higher compared to the NQFRWA scheme with shared protection. Furthermore, Figure 6-9 and Figure 6-10 also depict that the blocking probability using NQFRWA without protection is lower than that of using other schemes due to lack of reservation of wavelength channels for the fault resilience purpose.

From Figure 6-9 and Figure 6-10, we can summarize that QFRWA scheme outperforms NQFRWA scheme with dedicated protection in terms of resource utilization. The performance of the QFRWA scheme in terms of blocking probability is similar to the NQFRWA scheme with shared protection under blocking condition.

6.5.2 Non-blocking Case

Here, we will show the performance of the QFRWA scheme in terms of average reliability and Q-factor in the network under non-blocking. The results compared with two different schemes, namely, (i) NQFRWA with incorporation of dedicated protection, (ii) NQFRWA with incorporation shared protection and (iii) NQFRWA without protection. The average reliability and quality of signal (Q-factor) in the network are estimated using Equations (6.1) and (6.2) respectively. The reliability of each connection over a period of time , t is estimated as given in Equation (6.11) [112]. In this equation, f_p and f_s represent the failure rates of each primary path and backup path, respectively.

$$R(t) = e^{-f_p t} + \frac{f_p}{f_p - f_s}[e^{-f_s t} - e^{-f_p t}] \qquad (6.11)$$

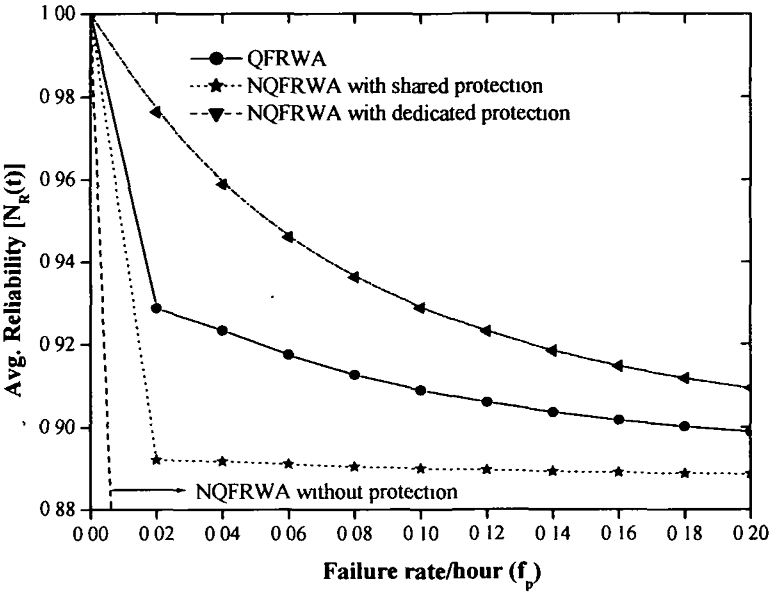


Figure 6-11: $N_R(t)$ versus f_p, obtained by using QFRWA and NQFRWA (without protection, with incorporation of dedicated and shared protections) schemes in the Indian network

Figure 6-11 and Figure 6-12 show the average reliability in the network versus failure rate in the primary path per hour, obtained by using QFRWA and NQFRWA (with incorporation of dedicated and shared protections) schemes in the Indian network and NSFNET, respectively. The average reliability in both networks has been estimated by using Equations (6.1) and (6.11) with 3000 con-

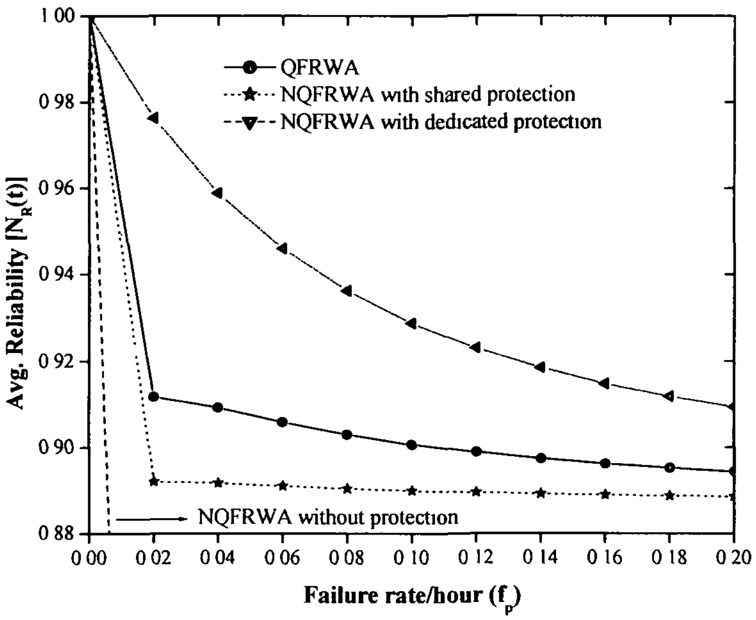


Figure 6-12: $N_R(t)$ versus f_p, obtained by using QFRWA and NQFRWA (without protection, with incorporation of dedicated and shared protections) schemes in NSFNET

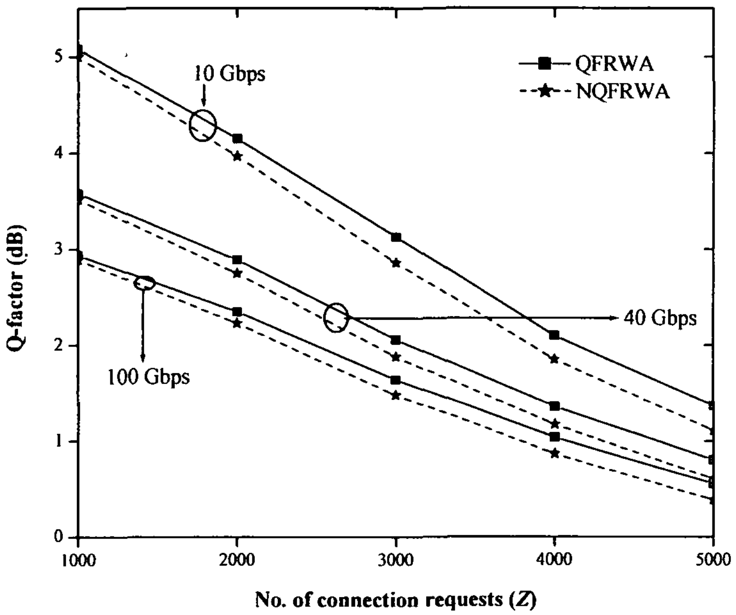


Figure 6-13: N_Q versus Z, obtained by using QFRWA and NQFRWA in the Indian network with different channel capacities

nection requests. It has been revealed from both the figures that in all cases, the average reliability decreases with increase in failure rate. For comparison purpose, in Figure 6-11 and Figure 6-12 we have incorporated the average reliability in

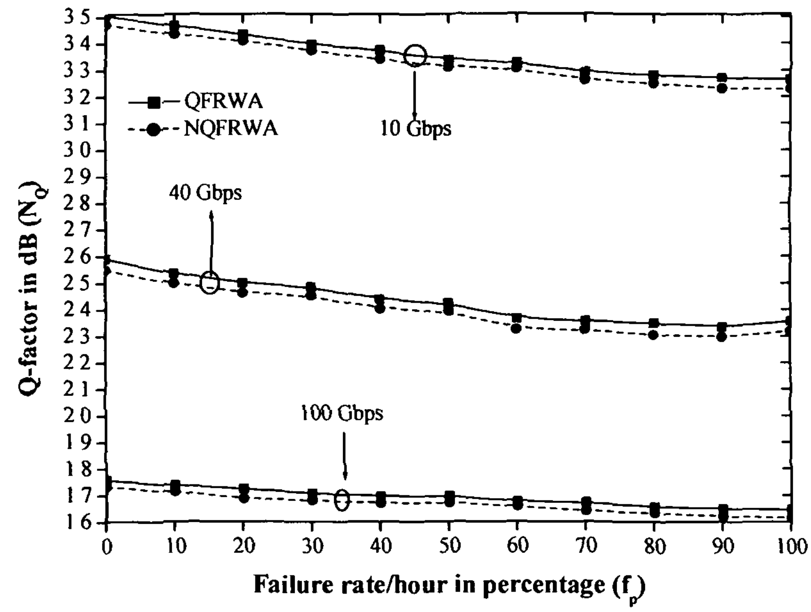


Figure 6-14: N_Q versus f_p (in percentage), obtained by using QFRWA and NQFRWA schemes in the Indian network with different channel capacities

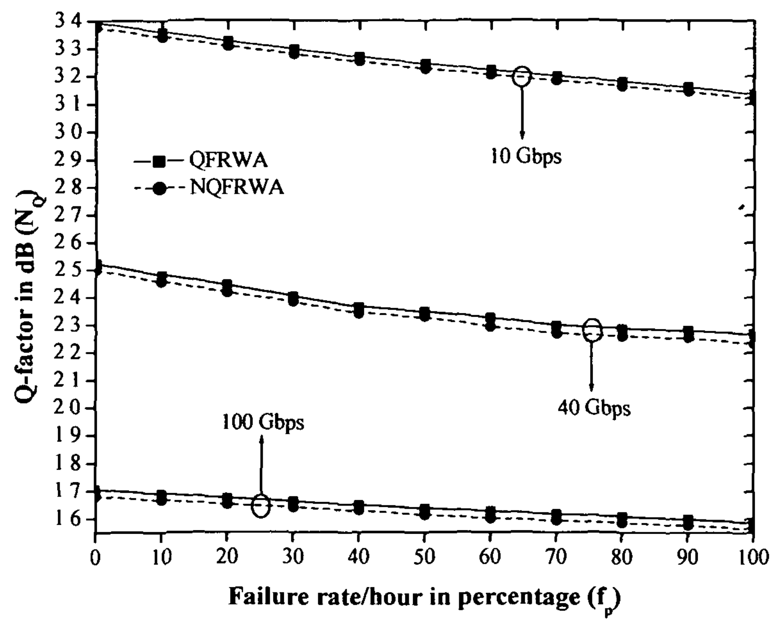


Figure 6-15: N_Q versus f_p (in percentage), obtained by using QFRWA and NQFRWA schemes in NSFNET with different channel capacities

the network using NQFRWA scheme without incorporation of protection. It can be observed from Figure 6-11 and Figure 6-12 that the average reliability drastically reduces with increase in failure rate, when no fault resilience technique is incorporated. It is evident from both the figures that the average reliability using the QFRWA scheme is higher than other schemes (except NQFRWA scheme with dedicated protection) due to restricted sharing of the backup paths in the sub branches of the protected trees for high reliability requirement connections. Furthermore, we found that the average reliability in the Indian network using QFRWA scheme is higher than that in NSFNET.

We have also studied the overall quality of the signal (Q-factor) versus the number of connection requests using QFRWA and NQFRWA schemes in the Indian network as shown in Figure 6-13. The overall Q-factor in the network using NQFRWA scheme with the incorporation of dedicated and shared protections remain almost the same. Therefore, during the analysis of Q-factor, we have considered only QFRWA and NQFRWA schemes. It is evident from the figure that the overall Q-factor decreases with increase in channel speed. This mainly occurs for dual imaging of the bits at the receiver side because of pulse broadening of shorter bit signal. From Figure 6-13, we can observe that the overall Q-factor in the network decreases with increase in number of connection requests. However, the rate of decrease in Q-factor using the QFRWA scheme is lower than that of using NQFRWA scheme. This is because, PDRWA scheme is used for the wavelength assignment in the QFRWA scheme without using any dispersion compensating device. Therefore, the overall signal quality (Q-factor) using QFRWA scheme has been improved reasonably compared to NQFRWA scheme, without substantial increase in network setup cost.

Figure 6-14 and Figure 6-15 show the overall Q-factor versus failure rate in the primary path per hour in percentage, estimated by using QFRWA and NQFRWA schemes in the Indian network and NSFNET, respectively. For this simulation study, we have generated 3000 number of connection requests. In the figures, solid and dashed lines represent the overall Q-factor in the network using QFRWA and NQFRWA schemes respectively. It has been revealed from the figures that the Q-factor decreases with increase in failure rate. However, the decrease rate using the QFRWA scheme is less than that of using NQFRWA scheme. This is because the total dispersion using the QFRWA scheme is less than that of using NQFRWA scheme. Furthermore, we found that the overall Q-factor decreases with increases in channel speed in the network.

From the above analysis, we can summarize that QFRWA outperforms NQFRWA in terms of the average reliability and overall signal quality, without substantial increase in network setup cost under non-blocking condition.

6.6 Conclusion

In this chapter, we have presented a QoS-aware fault resilience wavelength assignment (QFRWA) scheme for optical networks to improve network reliability, while maintaining better utilization of network resources and a better quality of signal (Q-factor). In this scheme, connection requests having the same source-destination pair are groomed first to avoid intermediate optical-electrical-optical conversion and then these groomed connection requests are served for lightpath establishment according to a PDRWA scheme to improve the signal quality. Finally, the established connections with higher reliability requirement are protected using reliable shared protection algorithm to provide higher reliability. The ordinary connections without extra reliability requirement are protected by shared protection for a better utilization of network resources. The effectiveness of the QFRWA scheme has been examined through performance evaluation in two example optical networks, namely, (i) the Indian network and (ii) NSFNET. From the simulation results we draw the following conclusions:

- Although the blocking probability in the fault resilience network using QFRWA scheme is slightly higher than that of using QFRWA scheme with shared protection, it provides a lower blocking compared to QFRWA scheme with dedicated protection.
- QFRWA scheme improves the average reliability in the network and significantly improves the quality of signal compared to NQFRWA scheme, without substantial increase in network setup cost.

Therefore, the QFRWA scheme will lead to a cost-effective solution for a high speed survival optical network design.

Chapter 7

Conclusion and Future Direction

This dissertation makes four important contributions to the body of knowledge on optical network planning problems, namely, routing and wavelength assignment (RWA), traffic grooming, quality of service provisional and network survivability. In this chapter, we summarize the main contributions made in this dissertation and provide direction for future works.

7.1 Conclusion

In this dissertation many aspects concerning WDM based optical networks have been investigated. We can distinguish our four research axes that have been addressed in this dissertation: (i) reducing the affect of wavelength continuity constraint during RWA approach, (ii) incorporating traffic grooming with RWA approach, (iii) QoS provision and (iv) fault management. Following conclusions are drawn from the contributions obtained in this dissertation.

7.1.1 Reduce the Affect of Wavelength Continuity Constraint

Wavelength continuity constraint plays an important role in WDM based optical networks which requires the use of same wavelength on all hops in the end-to-end path of a connection, without using wavelength converters. Use of a conventional RWA approach under the wavelength continuity constraint may lead to a situation where wavelengths may be available but connection requests cannot be established due to unavailability of the required wavelengths. In chapter 4 we have proposed a priority-based RWA (PRWA) scheme with incorporation of prioritization concept for reducing the affect of wavelength continuity constraint. As a result, the call blocking in the network has been reduced to a great extent, while maintaining the congestion level in the network. From the simulation study, it has been observed that the PRWA scheme significantly reduces the call blocking while maintaining the congestion level in the network, compared to non priority-based RWA scheme.

7.1.2 Incorporating Traffic Grooming with RWA Approach

It has been observed that majority of user applications require a much lower bandwidth (normally in Mbps range) than what a single wavelength channel can support. Therefore, traffic grooming mechanism has emerged as an emerging technology which has been incorporated with the RWA approach to further enhance the utilization of optical channel capacity. In chapters 4, 5 and 6 we have initially multiplexed a number of low-speed connection requests which belong to same source-destination pairs to avoid optical-electrical-optical conversion. The proposed traffic grooming mechanism outperforms the existing traffic grooming algorithms in terms of delay and network setup cost.

7.1.3 QoS Provision

One of the major issues related to the development of WDM based optical networks is QoS provision which considers how to improve signal quality (Q-factor) in the network. Dispersion in optical fiber degrades the quality of signal in optical networks. Although, dispersion compensating devices (like - Dispersion Compensating Fiber (DCF), Optical Phase Conjugation, Pulse Prechirping and Duobinary Transmission) are usually used to reduce dispersion, they are expensive. As an alternative solution, RWA approach can incorporate mechanisms to reduce the overall dispersion in the network. However, conventional wavelength assignment schemes of RWA approach do not take care of the reduction of dispersion in the network. In chapter 5, we have proposed a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme to reduce the overall dispersion in the network, without using any dispersion compensating device. As a result, the overall signal quality (Q-factor) has been improved, without substantial increase in network setup cost. The performance analysis of the PDRWA scheme using step-index fiber (SIF) has been conducted with three different channel speeds (10, 40 and 100 Gbps) in terms of total dispersion and the results are compared with the use of DCF. Further, We have studied the overall Q-factor in the network with different channel speeds and considering polarization mode dispersion (PMD) effect using SIF and DCF. From the simulation study, it has been observed that the total dispersion increases with channel speed. The rate of increase of total dispersion using PDRWA scheme is less than that of using a similar type of non dispersion-reduced wavelength assignment (NDRWA) scheme. As a result, the overall Q-factor in the network using the PDRWA scheme is improved compared to NDRWA scheme. Furthermore, it has been noticed that Q-factor (with PMD effect) while using PDRWA scheme with SIF has improved compared to PDRWA scheme with DCF, due to the higher PMD coefficient.

7.1.4 Fault Management

Recently, traffic grooming mechanism has emerged as an emerging technology which has been incorporated with the RWA approach to further enhance the utilization of optical channel capacity. As a result, nowadays a single fiber can carry a huge amount of information which is of the order of Tbps range. Therefore, failure of a network component, such as optical fiber, can disrupt communications for millions of users which can in turn lead to a greater loss of data and revenue Thus, the survivability against the failures has become an important requirement for optical networks. Therefore in our last work of chapter 6, we have incorporated a fault resilience scheme with priority-based dispersion-reduced wavelength assignment scheme to improve the network reliability, while maintaining a better utilization of network resources. The performance analysis of proposed fault resilience scheme is conducted through simulation study. The results of our simulation studies have shown that the proposed fault resilience scheme have improved the average reliability in the network, while maintaining a better utilization of network resources and better signal quality compared to existing schemes.

7.2 Future Direction

In this following, we outline some of the possible direction of future research works in this field of research.

- We have investigated the important linear impairments in PDRWA scheme.

Performance evaluation of PDRWA scheme in the context of all the physical-layer impairments needs further investigation which is left as part of future works.

- We have proposed schemes in this dissertation under wavelength continuity constraint. Incorporation of limited intelligent wavelength conversation with these schemes can further increase the performance of the network which is left as part of future works.

- We have proposed a QoS-aware fault resilience wavelength assignment scheme by considering the impact of protection technique. Incorporation of restoration technique with the fault resilience scheme may improve the network reliability and resource utilization which is left as part of future works.

- An optical network has the potential to fulfill the ever-increasing traffic demand. The high capacity of WDM based optical networks is assisted by the use of upper layers to aggregate low-rate traffic flows into the lightpaths in the form of traffic grooming. On the other hand, the traffic behavior changes rapidly and the increasing mobility of traffic sources makes grooming more complex. Therefore, in future, the effectiveness of WDM based optical networks may be reduced. In that scenario, flex grid technology or elastic optical network will play an important role to fulfill the ever-increasing traffic demand. The recasting of our proposed schemes for elastic optical networks are left as part of future works.

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Publications based on the Thesis Works

Journals

1. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "A QoS-aware Wavelength Assignment Scheme for Optical Networks", *Optik - International Journal for Light and Electron Optics (Elsevier)*, Vol. 124, no. 20, pp. 4498-4501, 2013, DOI: 10.1016/j.ijleo.2013.01.035. (SCI)

2. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "Review and Performance Analysis on Routing and Wavelength Assignment Approaches for Optical Networks", *IETE Technical Review*, Vol. 30, no. 1, pp. 12-23, 2013, DOI: 10.4103/0256-4602.107335. (SCI)

3. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "Priority based Dispersion-Reduced Wavelength Assignment for Optical Networks", *IEEE/OSA Journal of Lightwave Technology*, vol. 31, no. 2, pp. 257-263, 2013, DOI:10.1109/ JLT.2012.2228628. (SCI)

4. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "Priority based Routing and Wavelength Assignment with Traffic Grooming for Optical Networks", *IEEE/OSA Journal of Optical Communications and Networking*, vol. 4, no. 6, pp. 480-489, 2012, DOI:10.1364/JOCN.4.000480. (SCI)

5. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "A Heuristic Priority based Wavelength Assignment Scheme for Optical Networks", *Optik - International Journal for Light and Electron Optics (Elsevier)*, vol. 123, no. 17, pp. 1505-1510, 2012, DOI:10.1016/j.ijleo.2011.08.049. (SCI)

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6. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "Dispersion Reduction Routing and Wavelength Assignment for Optical Networks", *in the proc. of second International Conference on Trends in Optics and Photonics*, pp. 456 - 463, December 7-9, 2011, Kolkata, India.

7. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "A Priority Based Wavelength Assignment Scheme for Optical Network", Proc. of IWNMA - 2011, held with The 12th International Conference on Distributed Computing and Networking (ICDCN - 2011), Bangalore, pp 1-6, 2011.

Book Chapters

8. **Chatterjee, B. C.**, Sarma, N. and Sahu, P. P., "A Study on Routing and Wavelength Assignment Approaches for Optical Networks," *in Information and Communication Technology for Education, Healthcare and Rural Development*, ISBN: 978-81-8487-205-7, In: D. Goswami, S. Bhattacharya, F.A. Barbhuiya, and S. Chakraborty, Editors. India: Narosa Publishing House; pp. 88-100, 2012.