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Routing and Wavelength Assignment for WDM-based Optical Networks

Quality-of-Service and Fault Resilience

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Preface

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 nondeterministic polynomial time (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 book, 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 book makes important contributions to the development of WDM-based optical networks, concerning RWA problem, traffic grooming, network survivability, and quality-of-service provisioning.

In the near future, WDM-based optical transmission technology may be unable to fulfill the growing traffic demands as it suffers from the electrical bandwidth bottleneck limitation, and the physical impairments become more serious as the transmission speed increases. Moreover, the traffic behavior is changing rapidly, and the increasing mobility of traffic sources makes grooming more complex. In that situation, to manage the growing traffic demands is a challenging issue, which is the utmost importance for the optical researchers. This book introduces the limitations of convention WDM-based optical networks and then presents elastic optical networks for future high-speed communications.

This book starts with a brief introduction to optical networks and then moves into an overview of the existing works on lightpath establishment, routing, wavelength assignment, traffic grooming, quality of service, and fault resilience design in WDM-based wavelength-routed optical networks. The performance analysis of major conventional routing and wavelength assignment approaches in optical networks are presented to understand the behavior of routing and wavelength assignment approaches. Thereafter, a priority-based routing and wavelength assignment scheme with the incorporation of a traffic grooming have been presented in order to reduce the call blocking in the network. We discuss a priority-based dispersion-reduced wavelength assignment scheme with incorporation of traffic grooming to achieve the reduction of the total dispersion in the network, and hence, the overall signal quality is improved without substantial increase in network setup cost. Furthermore, a reliable fault resilience scheme is presented to improve the reliability in the network; the reliable fault resilience scheme provides a new class of service, which trade offs between network reliability and blocking probability. Finally, we present the limitations of convention WDM optical networks and provide how elastic optical networks overcome these limitations.

Many electrical engineering, computer engineering, and computer science programs around the world have been offering a graduate course on optical networking. This book primarily targets both graduate and doctoral students who are interested to consider their research in routing and wavelength assignment topic. Using this book, students will understand both fundamental and advanced technologies on routing and wavelength assignment for optical networks. This book is also intended for optical networking professionals, R&D engineers, and network designer, who are currently active or anticipate future development of optical networks. This book allows them to design a cost-effective optical network while improving the network performances, such as call blocking, quality of service, and reliability.

We are thankful to Springer for giving us the opportunity to publish this book. We acknowledge the love and affection from our families. This project would not have been successfully completed without their understanding, support, and patience. Although utmost care has been taken in the preparation of the manuscript, chances of an error cannot be ruled out. It would be highly appreciated if the reader can find sometime to send any suggestion to the authors.

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Introduction to Optical Network

1.1 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 Fig. 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. To fulfill our ever-increasing bandwidth demand, all optical backbone networks along with wavelength-division multiplexing (WDM) technology are essential, this is due to their many desirable properties including higher bandwidth availability, low signal attenuation, low signal 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 [2], fiber distributed data interface [3], token-ring [4], ethernet [5], and synchronous optical networking/synchronous digital hierarchy [6] 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.

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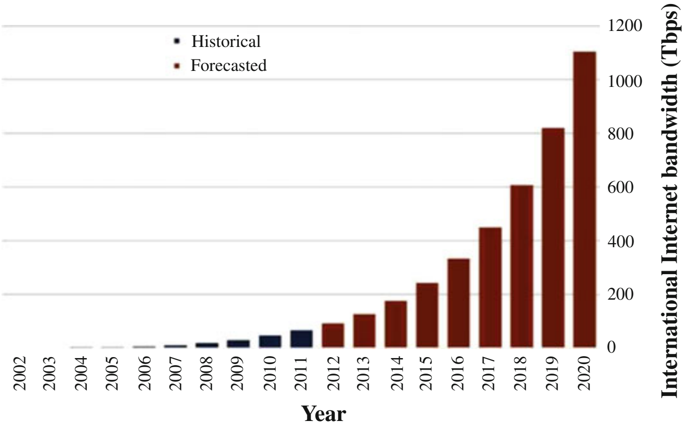

Fig. 1.1 Used international internet bandwidth, 2002–2020 [1]

1.1.1 Synchronous Optical Networking/Synchronous Digital Hierarchy

Synchronous optical networking or synchronous digital hierarchy [7] 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 [8] 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 Fig. 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

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

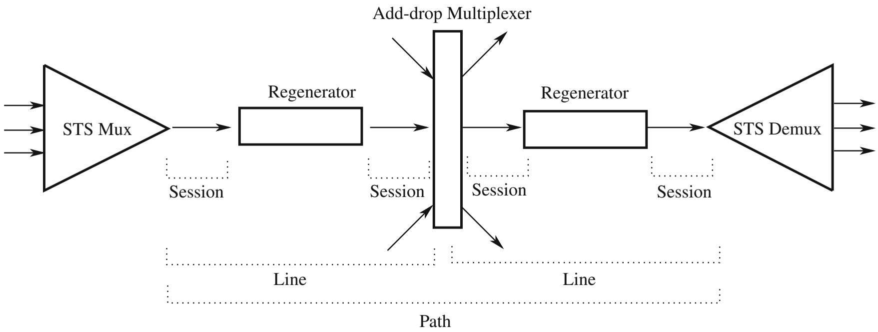

Fig. 1.2 Concept of SONET system

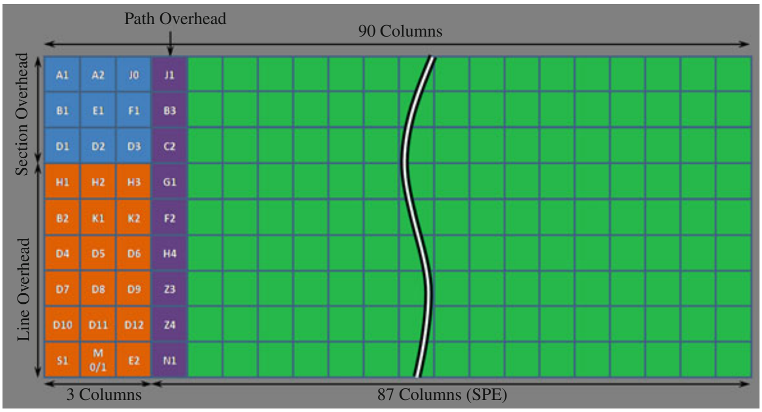

Fig. 1.3 SONET STS-1 frame format [9]

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.

1.2 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.

1.2.1 Broadcast-and-Select Optical Networks

Broadcast-and-select optical networks [7, 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.

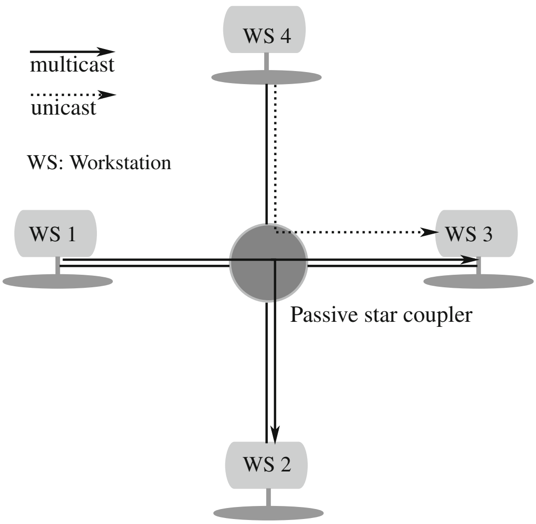

Fig. 1.4 A passive-star-based local optical network

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.

1.2.2 Wavelength-Routed Optical Networks

Wavelength-routed optical network [7, 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 [7, 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 [7, 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 [7, 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 [7, 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.

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

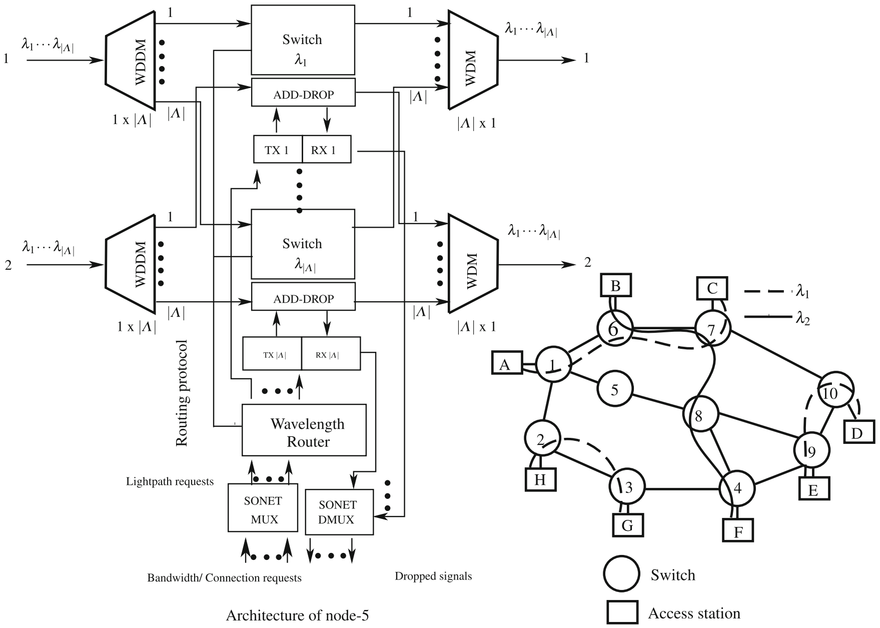

Fig. 1.5 A wavelength-routed optical network

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

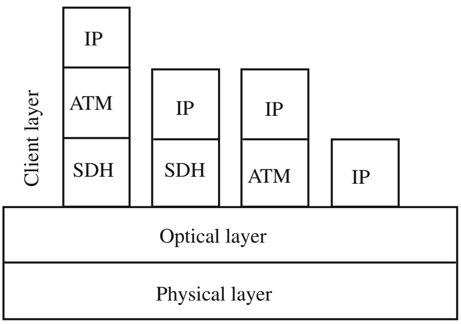

Fig. 1.6 Layers of a WDM based wavelength-routed optical network

the possible layers in a WDM based wavelength-routed optical network which are discussed below.

- 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 and provide quality of service to the end-users.
- 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.
- 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].

1.3 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 Fig. 1.8. Total internal reflection theorem has been used in optical fiber to propagate the optical signal from transmitter to receiver.

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

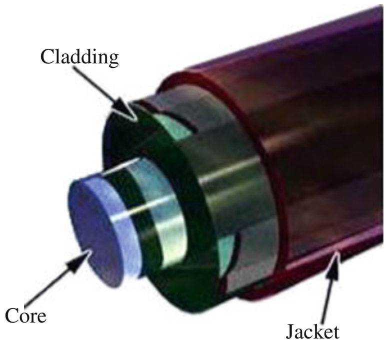

Fig. 1.7 Physical structure of an optical fiber

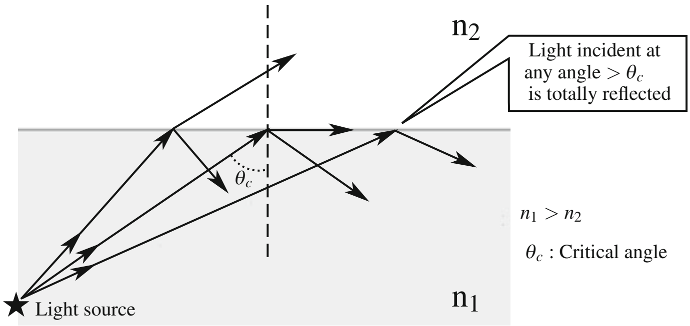

Fig. 1.8 Reflection and refraction of light pulse

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.

1.3.1 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 $10 \times \log_{10}$(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 μ. Among these bands, C band (1.530–1.565 μ) and L band (1.565–1.625 μ) 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

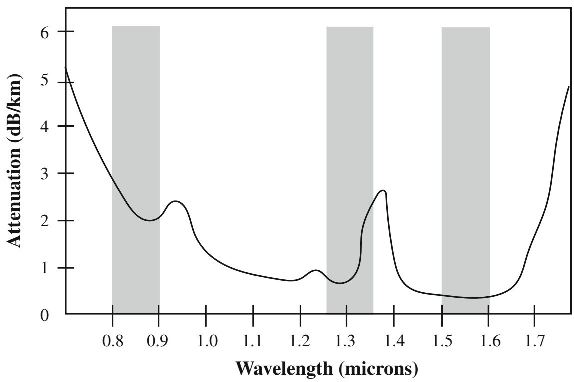

Fig. 1.9 Attenuation versus wavelength for optical fiber

to reduce dispersion, they are very expensive. The effects of these linear impairments will be discussed in Chap. 6.

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].

1.4 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) [7, 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 Fig. 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.

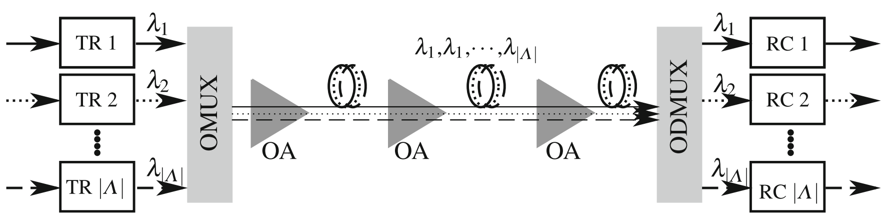

Fig. 1.10 Concept of wavelength division multiplexing

1.5 Basic Components of WDM Optical Networks

In this section, we briefly discuss about various major components [7, 10, 12, 15–17] that 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.

- 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.
- 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 Fig. 1.11. Total internal reflection theorem of light is being applied to propagate signal from transmitter to receiver, which is already explained in Sect. 1.3.
- 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.
- 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 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].

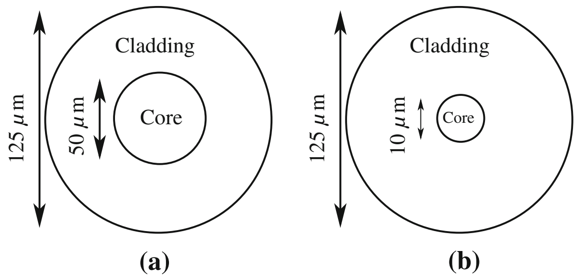

Fig. 1.11 Cross sections of **a** multimode and **b** single mode fibers

- 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 × 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 Fig. 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 (−50–70 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.
- 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 Fig. 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.

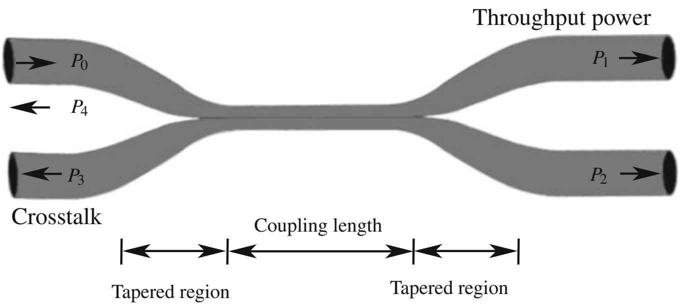

Fig. 1.12 2 × 2 optical coupler

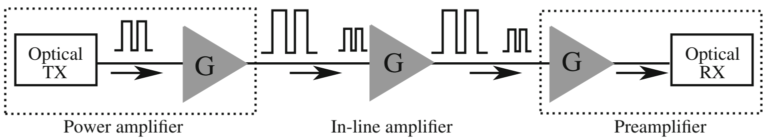

Fig. 1.13 Applications of optical amplifiers

– **Power amplifier**: Power amplifier is placed immediately after the optical transmitter to boost the transmitted power.

- 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].
- 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.
- Optical supervisory channel: Optical supervisory channel (OSC) [15] is a separate wavelength/channel, usually placed outside the amplification band (at 1310, 1510 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.
- 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 × 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 Fig. 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

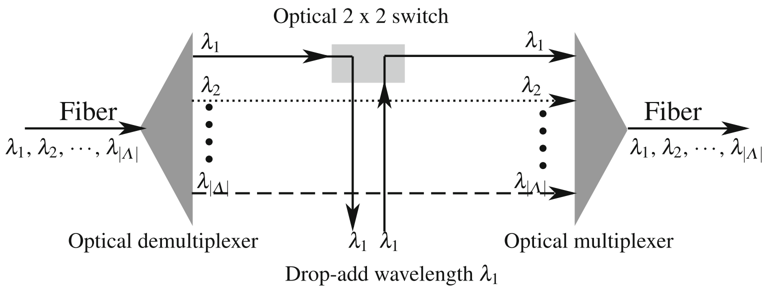

Fig. 1.14 Optical add-drop multiplexer

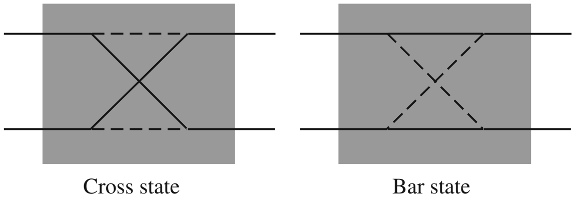

Fig. 1.15 2×2 crossconnect elements in the cross state and bar state

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.

- 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].

1.6 Current Research Issues and Challenges

Routing and wavelength assignment (RWA) [7, 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 WDM-based 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 lightpath request cannot be established due to unavailability of a specific wavelength.
- The quality of transmission degradation due to the dispersion effect is a critical issue in optical networks. Although dispersion compensation devices reduce

the effect of dispersion, they require an additional cost. Impairment-aware RWA without using any dispersion compensation device in order to satisfy the required signal quality level at the receiver side is a hot research topic, which needs further research.

- Existing fault resilience techniques [21, 22] are unable to handle multi-failure simultaneously. Incorporating fault resilience technique with the RWA approach in order to improve the network reliability by handling multi-failure simultaneously is one of the research issues for optical domain.

In the near future, WDM-based optical transmission technology may be unable to fulfill the growing traffic demands as it suffers from the electrical bandwidth bottleneck limitation, and the physical impairments become more serious as the transmission speed increases [14]. Moreover, the traffic behavior is changing rapidly and the increasing mobility of traffic sources makes grooming more complex. In that situation, to manage the growing traffic demands is a challenging issue, which is the utmost importance for the optical researchers.

1.7 Organization of the Book

In the following, we briefly outline the organization of this book.
Chapter 1: *Introduction* — This chapter provides a brief introduction to optical networks and explaining the current research issues and challenges for optical network.
Chapter 2: *Literature survey* — This chapter presents 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: *End-to-end traffic grooming* — To enhance the channel utilization in optical networks, this chapter introduces an end-to-end traffic grooming mechanism, which multiplexes the connection/bandwidth requests that having the same source-destination pair into a lightpath within the channel capacity.
Chapter 5: *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 introduced in this chapter to achieve the reduction of call blocking in the networks.
Chapter 6: *Priority-based dispersion-reduced wavelength assignment scheme* — This chapter introduces a priority based dispersion-reduced wavelength assignment (PDRWA) scheme for optical networks in order to reduce overall dispersion in the network without using any dispersion compensation device, and hence the overall Q-factor in the network is improved.
Chapter 7: *A reliable fault resilience scheme* — This chapter introduces a tree-based fault resilience scheme to improve the network reliability for optical networks.

Chapter 8: *Limitations of conventional WDM optical networks and elastic optical networks for possible solutions* — This chapter introduces the limitations of convention WDM based optical networks, and then presents elastic optical networks for future high-speed communications.

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Chapter 2
Literature Survey

2.1 Introduction

This book 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 book. 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 Sect. 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, Sect. 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 [1–5] namely, (i) static traffic and (ii) dynamic traffic have been considered for routing and wavelength assignment (RWA) purpose, which are discussed below.

B.C. Chatterjee et al., *Routing and Wavelength Assignment for WDM-based Optical Networks*, Lecture Notes in Electrical Engineering 410, DOI 10.1007/978-3-319-46203-5_2

- In case of static traffic assumption [1, 6], 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 [4–6], 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 higher 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 [7–11] have investigated the SLE problem to establish a static set of lightpaths in optical networks. In this direction, R. Ramaswami et al. [10] formulated static RWA problem as an NP-hard problem. I. Chlamtac et al. [12] 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 [12, 13] 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 [14]. Therefore, efficient heuristic approaches are the possible ways to tacle this difficult problem. In this direction, G. Shen et al. [15] and R. Ramamurthy et al. [16] 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 Sects. 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 [17], (ii) fixed alternate routing [18], (iii) adaptive routing [19–21], and (iv) least congested routing [22]. These routing approaches have mainly considered to find out the suitable end-to-end routes between source-destination pairs. Among these algorithms, fixed routing is considered to be the simplest among all, whereas adaptive routing provides the best performance in terms of call blocking. Fixed alternate routing 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

In fixed routing (FR), a single fixed end-to-end route is pre-computed for each source-destination pair using some shortest path algorithms, such as Dijkstras algorithm [23]. 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.

[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.

2.3.2 Fixed Alternate Routing

Fixed alternate routing (FAR) 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

Least congested routing (LCR) 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

In adaptive routing (AR), 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 Fig. 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.

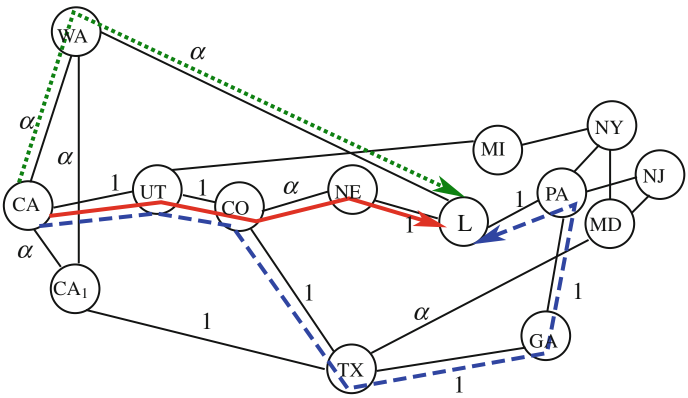

Fig. 2.1 Fixed/primary (*solid-red line*), alternate (*dotted-green line*) and adaptive (*dashed-blue line*) routes are shown between source city CA to destination city L

Table 2.1 Summaries of different routing algorithms

Problem	Approach		Ref	Performance analysis			On/Off line
				BP	AST	TC	
Routing + First-fit	Static	FR	[17]	Higher BP than others	Lower AST than others	O $(L_1 \cdot W \cdot Z)$	Off line
		FAR	[18]	Lower BP than FR	Higher AST than FR	O $(L_2 \cdot K \cdot W \cdot Z)$	Off line
		LCR	[22]	Almost same as FAR	Almost same as FAR	O $(L_3 \cdot K \cdot W \cdot Z)$	Off line
	Dynamic	AR	[19]	Lower BP than others	Higher AST than others	O $(L_2 \cdot N^2 \cdot W \cdot Z)$	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

Significant amount of works addressing different issues of routing have been reported in the literature. Table 2.1 [24–26] summaries the major routing algorithms, comparing their performance in terms of blocking probability (BP),[2] average setup time (AST)[3] and time complexity (TC).

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 [6, 27–42]. Among these heuristics, some significant heuristics, such as first fit, least used, most used, and random wavelength assignment policies are briefly discussed in the following subsections.

2.4.1 First Fit

In first fit (FF) policy [6, 27–30], the wavelengths are indexed and a list of indexes of available and used wavelengths is maintained. This policy 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 policy, no global information of the network is required. FF wavelength assignment policy is considered to be one of the best policy due to its lower call blocking and computational complexity.

[2]The blocking probability is defined as a ratio of the number of blocked connection/bandwidth requests to the number of connection/bandwidth requests in the network.

[3]The average setup time is defined as a ratio of total execution time in the network to the number of successful connections.

2.4.2 Least Used

Least used (LU) policy [6, 27, 29] 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 policy 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

Most used (MU) policy [6, 27, 29] 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 policy 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

In random (R) policy [27–29], a list of free or available wavelengths is maintained. When a connection request arrives in the network, this policy 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 policies, we use an example network segment as shown in Fig. 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 policy 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 policies, respectively. Random policy selects any of the two wavelengths with an equal probability.

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 policies comparing their performance in terms of two major parameters, namely, blocking probability (BP) and time complexity (TC).

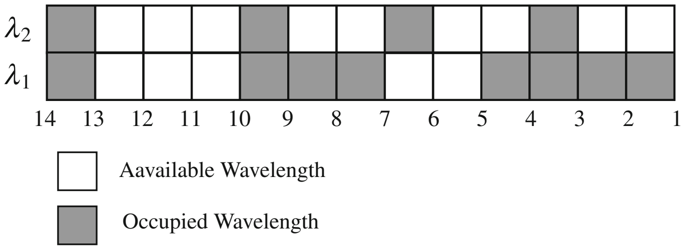

Fig. 2.2 Wavelength-usage pattern for a network segment

Table 2.2 Summaries of different wavelength assignment policies

Problem	Approach	References	Performance analysis		Applicable NW
			BP	TC	
Wavelength assignment + Fixed routing	Max Sum (MS)	[29]	In multi-fiber, MS outperforms when load is high	O $(L_1 \cdot W \cdot N^3 \cdot Z)$	Single/multi-fiber networks
	Relative Capacity Loss (RCL)	[29]	In single fiber, RCL performs well when load is high	O $(L_1 \cdot W \cdot N^3 \cdot Z)$	Single/multi-fiber networks
	Min product (MP)	[29]	MP performs well under low load	O $(L_1 \cdot M \cdot N \cdot W \cdot Z)$	Normally used in multi-fiber networks
	Least-loaded (LL)	[29]	LL performs well under high load	O $(L_1 \cdot M \cdot N \cdot W \cdot Z)$	Normally used in multi-fiber networks
	Least used (LU)	[6, 27, 29]	LU perform well under high load	O $(L_1 \cdot E \cdot W \cdot Z)$	Single/multi-fiber networks
	Most used (MU)	[6, 27, 29]	MU perform well under low load	O $(L_1 \cdot E \cdot W \cdot Z)$	Single/multi-fiber networks
	Random (R)	[27–29]	Higher BP than FF but almost close	O $(L_1 \cdot W \cdot Z)$	single/multi-fiber networks
	First fit (FF)	[28–30]	Lower BP among LU, MU, R	O $(L_1 \cdot W \cdot Z)$	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 [43]. 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 [27, 44–46, 46–51] 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 [50] 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.

A.L. Chiu et al. [45] proved that the traffic grooming problem in WDM based optical network is NP-complete [23]. They shown that the bin packing problem can be transformed into the traffic grooming problem within a polynomial time. However, integer linear programming (ILP) formulation can be used to obtain an optimal solution for a smaller size network. In this direction, J. Wang et al. [47, 51] 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, K. Zhu and B. Mukherjee [27, 50] presented 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.

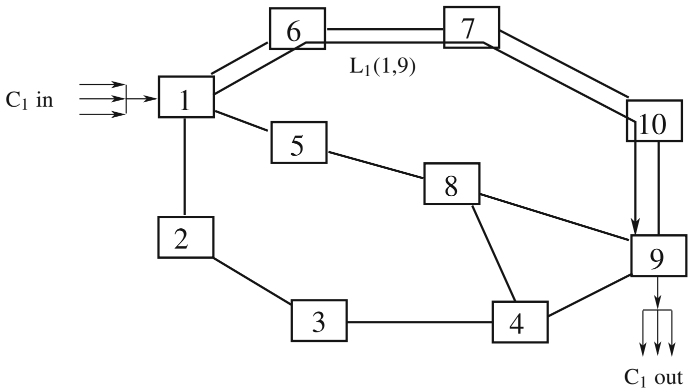

Fig. 2.3 Example of single-hop traffic grooming

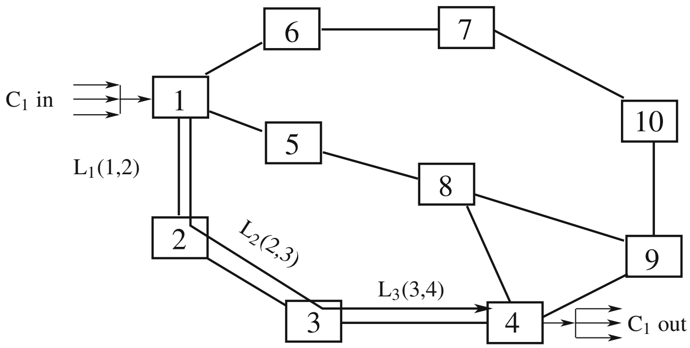

Fig. 2.4 Example of multi-hop traffic grooming

Table 2.3 Summaries of different traffic grooming mechanisms

Problem	Traffic	References	Network architecture	Outcomes
Wavelength assignment + Fixed routing	Dynamic and static	[52, 53]	Single-hop and multi-hop optical ring	(i) Minimizing transceiver cost (ii) Study of dynamic traffic
	Egress and static	[45]	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	[54, 55]	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	[56]	Unidirectional and bi-directional ring (single-hop)	(i) Greedy heuristic for grooming arbitrary traffic (ii) Heuristic for circle construction for non-uniform traffic.
	Static	[27, 47]	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	[57–59]	Multi-hop mesh network	(i) Maximize channel utilization (ii) Maximize network throughput
	Poisson	[6, 27]	Single-hop mesh network	(i) Maximize channel utilization

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 [27, 50]. 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.

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 [59]. 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 [60] 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 [60], if the network is capable to recover failure in the event of a fault occurrence. Many studies [27, 61–64] have been carried out for fault management in WDM based optical networks. In this direction, D. Zhou et al. [61] and S. Sengupta et al. [65] summarized the solutions of recovery mechanisms for ring and mesh based optical networks. WDM based optical networks incorporate two types of fault recovery techniques [27, 60, 64], 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. S. Ramamurthy et al. [66] 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, H. Choi et al. [67], M. Clouqueur et al. [68], N. Bao et al. [69], and V.Y. Liu et al. [70] 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 [27, 60], a dedicated path is reserved for each working path, an example of this is shown in Fig. 2.5. It has been observed from the literature survey that two types of dedicated protection [27, 60], namely, (i) 1+1 protection and (ii) 1:1 protection have been mainly considered for recovery purpose.

- **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

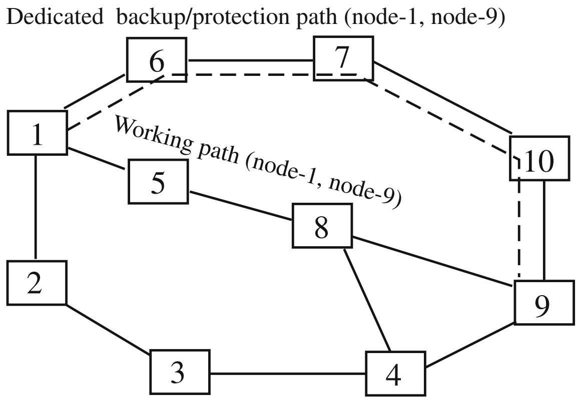

Fig. 2.5 Example of dedicated backup/protection path from node-1 to node-9

or the failure-detection time. If the kth bit of data reaches the destination at time, say t_2, through the working path, the same kth 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 $(k - l)$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 kth 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 [27, 60] 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 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.

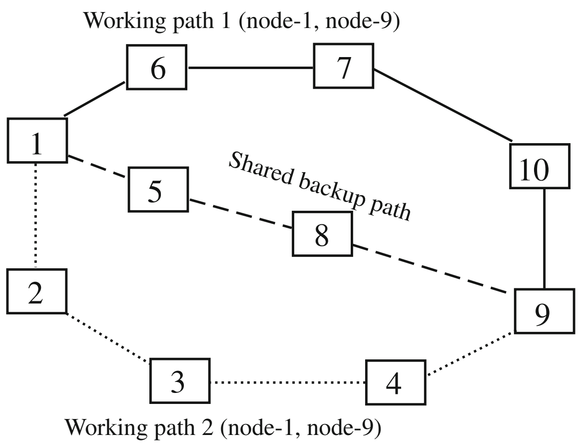

Fig. 2.6 Example of shared backup/protection path from node-1 to node-9

2.6.2 Restoration

In restoration [27, 60, 64, 71, 72], 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 [64] discovers a backup path of the failed connection only around the failed link. In path restoration [64], the failed connection independently discovers a backup path on an end-to-end basis. Segment-based restoration [64] 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

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

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Chapter 3
Performance Analysis of Major Conventional Routing and Wavelength Assignment Approaches

3.1 Introduction

Routing and wavelength assignment (RWA) [1, 2] is considered to be one of the key functionality for wavelength division multiplexing (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 or bandwidth request. If a connection/bandwidth request cannot be established within holding time, which is supplied by the network designer according to user requirement and the connection request should be established within this time, it is treated as a blocked connection/bandwidth request. 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 [3]. 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 book. In this section, we also address the model assumptions, which are used throughout this chapter. The performance of major conventional RWA approaches is evaluated through simulation study in Sect. 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, Sect. 3.4 concludes this chapter.

3.2 Model and Assumptions

We model the optical network as a connected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has an order set $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\}$ of wavelengths. The following assumptions are considered in our model.

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- Each fiber link can carry an equal number of wavelengths, and the network is without wavelength conversion capabilities.
- Two lightpaths sharing at least one fiber link are allocated with different 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 not capable of multiplexing/demultiplexing.

3.3 Performance Analysis

This section evaluates the performance of some major conventional RWA approaches. We consider 14 nodes with 24 bi-directional physical links of the Indian network (see Fig. 3.1) [4] and 14 nodes with 21 bi-directional physical links of NSFNET

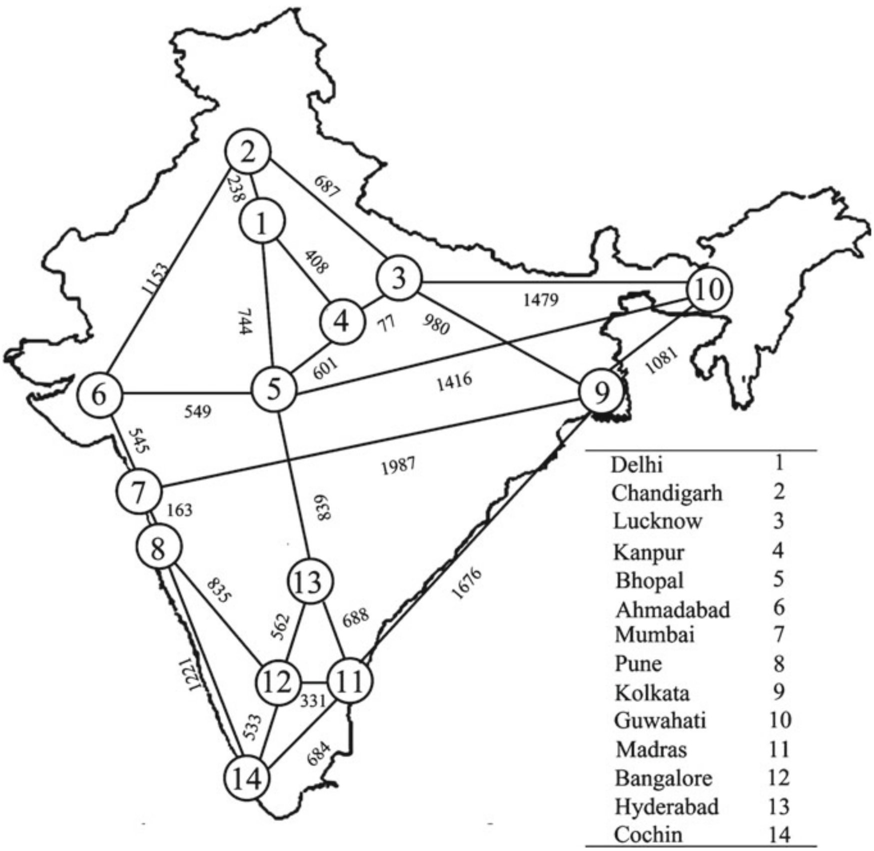
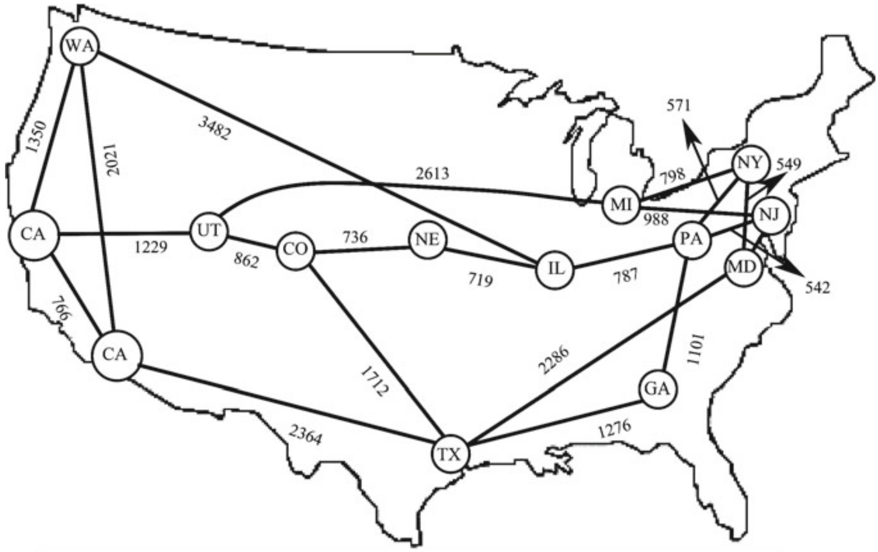


Fig. 3.1 Indian network and distances between its adjacent cities in kilometers



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

Fig. 3.2 National Science Foundation Network (NSFNET) and distances between its adjacent cities in kilometers

[1] (see Fig. 3.2) as network topologies. The following assumptions are considered for the purpose of simulations. The routes between a source-destination pair are found using the K-shortest paths [5] algorithm. During the wavelength assignment we consider traffic according B-Erlang formula [6, 7], as shown in Eq. (3.1). The connection/bandwidth requests are generated randomly based on a Poisson process with λ arrival rate and the holding times, denoted by h, of these connection/bandwidth requests are exponentially distributed.

$$p_b = \frac{\frac{E^m}{m!}}{\sum_{i=0}^{m} \frac{E^i}{i!}}, \tag{3.1}$$

where p_b is the probability of blocking, m is the number of wavelength resources. $E = \lambda h$ is the normalised ingress load (offered traffic stated in erlang).

3.3.1 Routing

This subsection evaluates the performance of routing algorithms in terms of blocking probability and average setup time. The blocking probability is defined as a ratio of the number of blocked connection/bandwidth requests to the number of connection/bandwidth requests in the network. The average setup time is defined as a ratio of total execution time in the the network to the number of successful connections. For wavelength assignment purpose, we consider first-fit (FF) policy [1, 2] due to its lower call blocking and computational complexity compared to other wavelength assignment policies.

Figures 3.3 and 3.4 show the blocking probability versus the number of wavelengths in the Indian network and NSFNET, respectively, when the traffic load is

Fig. 3.3 Blocking probability versus $|\Lambda|$ for the different routes (K values) in Indian network

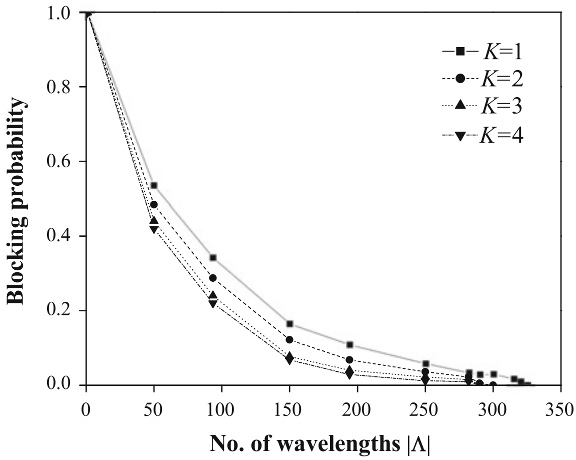
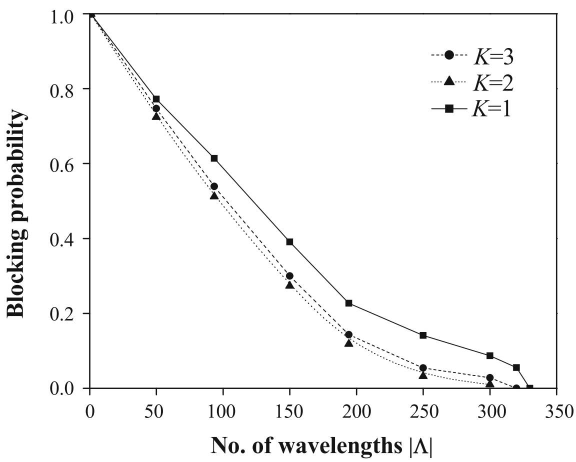


Fig. 3.4 Blocking probability versus $|\Lambda|$ for the different routes (K values) in NSFNET



considered 100 Erlang. 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 revealed that in both the networks, the blocking probability decreases with increase in number of wavelengths. On the other hand, the blocking probability also decreases with the increase in number of routes. 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 routes in the Indian network. Similarly, in NSFNET, the variation of blocking probability using up to two (i.e. $K = 3$) alternate routes is close to that of using up to one (i.e. $K = 2$) alternate route.

Figures 3.5 and 3.6 show the average setup time versus number of wavelengths for the different routes in the Indian network and NSFNET, respectively, with 100

Fig. 3.5 Average setup time versus $|\Lambda|$ for the different routes in Indian network

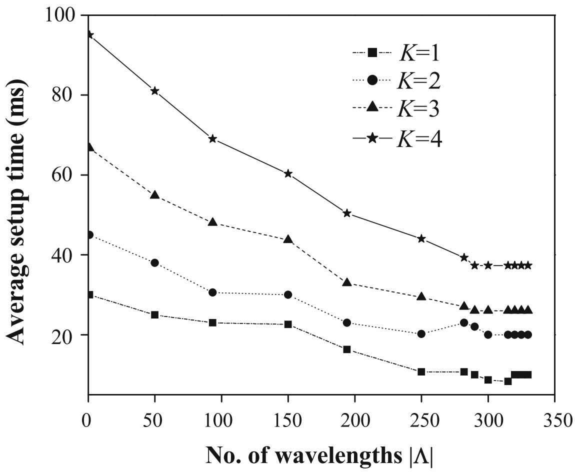
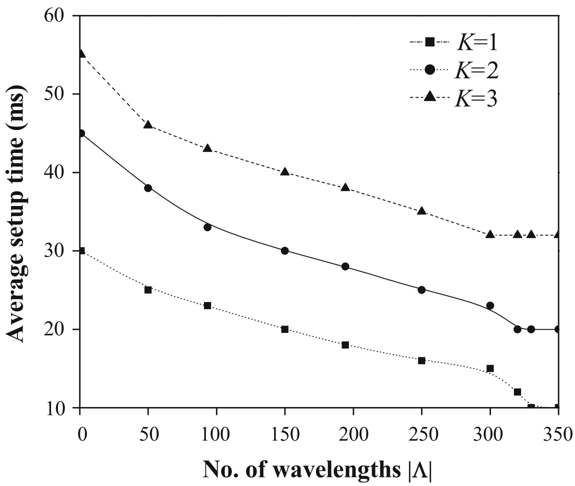


Fig. 3.6 Average setup time versus $|\Lambda|$ for the different routes in NSFNET



Erlang traffic volume. It has been observed from Figs. 3.5 and 3.6 that the average setup time increases with increase in number of alternate routes. This is mainly due to extra time required to find the next alternate route. However, the average setup time of different routes 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.

By analyses of Figs. 3.3, 3.4 and 3.5, we can summarize that as the number of alternate routes 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 routes 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.

Figures 3.7 and 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 network and NSFNET, respectively, with 100 Erlang traffic volume. 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 Figs. 3.7 and 3.8 that the blocking probability decreases with increase in number 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.

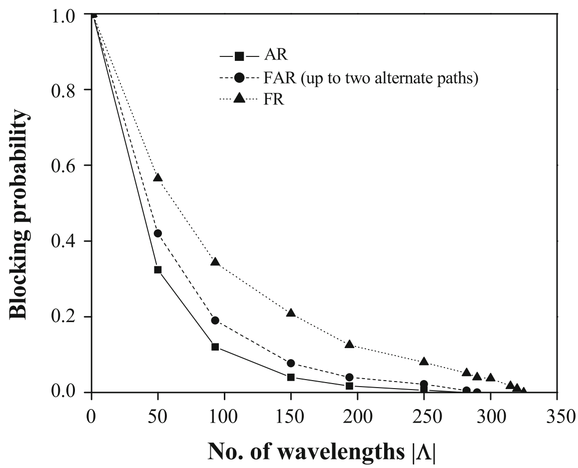


Fig. 3.7 Blocking probability versus $|\Lambda|$ for the different routing algorithms in Indian network

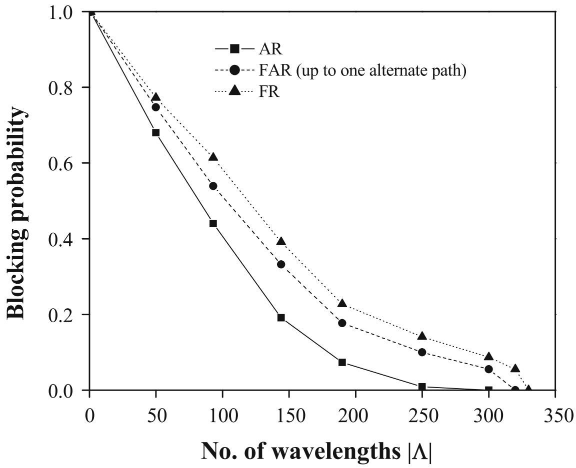


Fig. 3.8 Blocking probability versus $|\Lambda|$ for the different routing algorithms in NSFNET

3.3.2 *Wavelength Assignment*

This subsection evaluates the performance of wavelength assignment policies, 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 policies, 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 policies. Therefore in our simulation study, we have only considered FF, Random and LU wavelength assignment policies.

Figures 3.9 and 3.10 show the blocking probability versus number of wavelengths using different wavelength assignment policies in the Indian network and NSFNET,

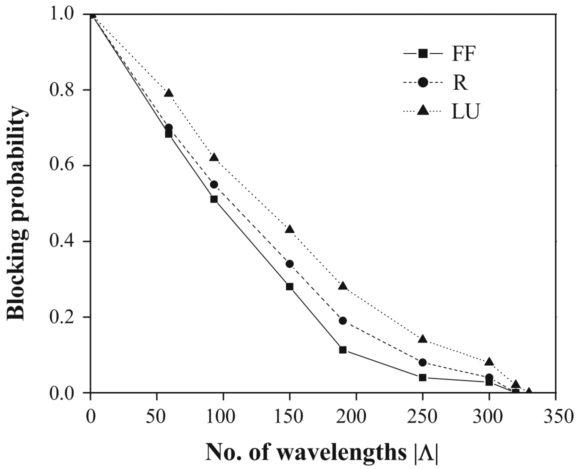
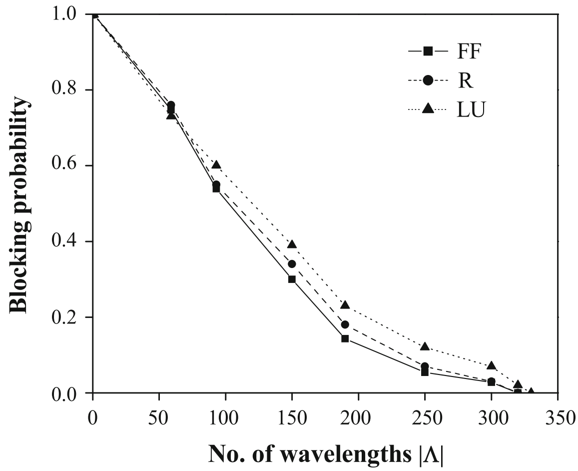


Fig. 3.9 Blocking probability versus $|\Lambda|$ for the different wavelength assignment policies in Indian network

Fig. 3.10 Blocking probability versus $|\Lambda|$ for the different wavelength assignment policies in NSFNET



respectively, with 100 Erlang traffic volume. It has been revealed from Figs. 3.9 and 3.10 that the blocking probability decreases with increase in number of wavelengths irrespective of the wavelength assignment policy used. However, the rate of decrease in blocking probability using FF policy is more than that of using other policies. 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 Figs. 3.9 and 3.10 that the blocking probability using random wavelength assignment policy 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 policy.

3.4 Conclusion

This chapter analyzed the performance of major routing algorithms and conventional wavelength assignment policies in wavelength-routed optical networks. We observed that the performance of first-fit wavelength assignment approach in terms of blocking probability is the best among all the wavelength assignment policies considered. Although adaptive routing with first-fit wavelength assignment policy provides the lowest 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 100 Erlang traffic volume, a large number ($\sim$350) of wavelengths are required, which are 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.

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Chapter 4
End-to-End Traffic Grooming

4.1 Introduction

Wavelength routing together with wavelength division multiplexing (WDM) technology have been considered as a strong candidate for next generation high performance networks. WDM technology has provided tremendous bandwidth of the optical fiber by allowing simultaneous transmission of traffic on many non-overlapping wavelength channels in a optical fiber. Nowadays, majority of connection requests are still in Mbps range. If a connection request is dedicatedly assigned to a wavelength channel, the capacity of the wavelength channel is not utilized, which decreases the efficiency of the network. This problem can be overcome by incorporating traffic grooming [1–6] mechanism. The traffic grooming mechanism is incorporated with routing and wavelength assignment (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.

Taking this direction, K. Zhu et al. [2] studied the traffic-grooming problem in a WDM mesh network. They provided the architecture of a node with grooming capability and compared the performance of single-hop grooming with multi-hop grooming. Finally, the authors presented two heuristics on traffic grooming, namely, (i) maximizing single-hop traffic and (ii) maximizing resource utilization, to increase the network throughput for large networks.

Multi-hop traffic grooming aggregates calls on several lightpaths to enhance the channel utilization. Connections from different source-destination pairs share the bandwidth of a lightpath. The multi-hop grooming provides the best performance in terms of resource utilization and blocking characteristics, but it can only be implemented using the opaque technology. As a result, it requires a significant amount of electronic processing, such as optical-electrical-optical conversion at each hop, which produces traffic delay in the network and requires additional cost.

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As the multi-hop or hop-wise traffic grooming requires optical-electrical-optical conversion at each hop, which introduces additional cost, this chapter focuses on an end-to-end traffic grooming [7–10], where initially a number of low-speed connection requests that belong to same source-destination pairs are multiplexed, in order to avoid optical-electrical-optical conversions at each hop.

The rest of the chapter is organized as follows. Section 4.2 describes the model and assumptions. Section 4.3 presents the network grooming node architecture, and describes the functionality of components of a network node. The end-to-end traffic grooming is presented in Sect. 4.4. Section 4.5 evaluates the performance of the end-to-end traffic grooming. Finally, Sect. 4.6 concludes this chapter.

4.2 Model and Assumptions

We model the optical network as a connected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has an order set $\Lambda=\{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\}$ of wavelengths. The following assumptions are considered in our model.

- Each fiber link can carry an equal number of wavelengths, and the network is without wavelength conversion capabilities.
- Two lightpaths sharing at least one fiber link are allocated with different 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/bandwidth requests having the same source-destination pair as possible within the channel capacity.

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 hops 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.

Figure 4.1 shows the logical architecture of the network node which uses a number of devices, such as wavelength division multiplexers (WDMs)/wavelength division demultiplexers (WDDMs), thermo-optic switches (TOSWs), transmitters (TXs), receivers (RXs), add-drop multiplexers (ADMs), a synchronous optical networking (SONET) synchronous transport signal (STS) multiplexer (SONET MUX)/SONET STS demultiplexer (SONET DMUX), and a wavelength router. The functions performed by a network node are consists of three tasks that are explained briefly as follows:

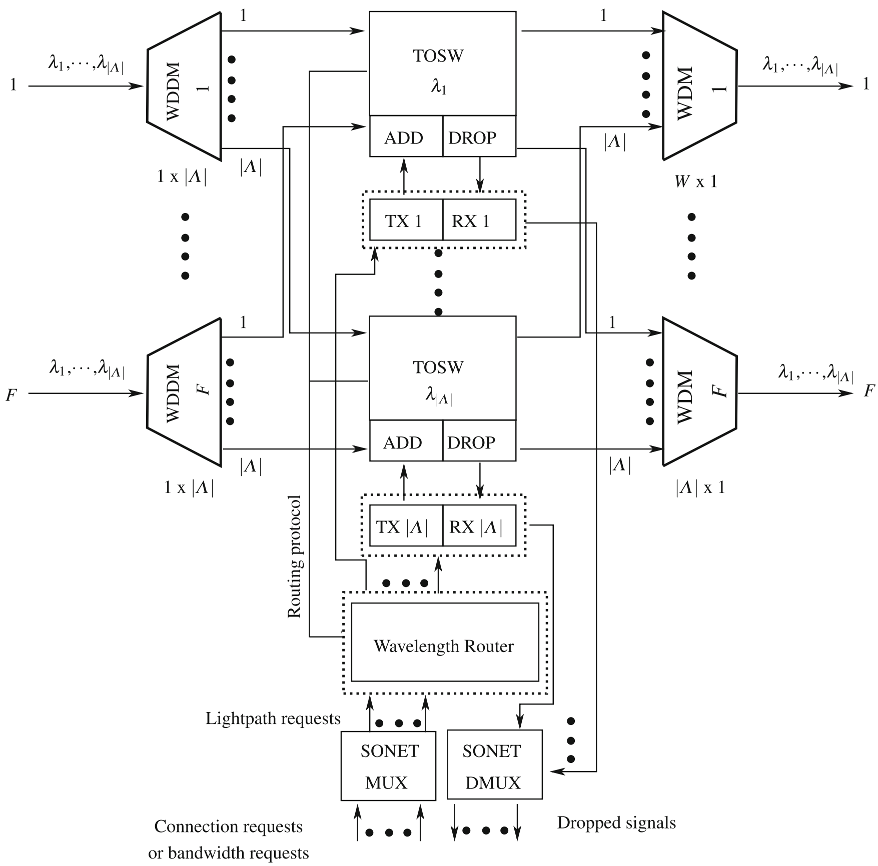

Fig. 4.1 Node architecture

(i) Initially, several connection requests or bandwidth requests arrive at the system randomly based on any distribution. The connection requests or bandwidth requests having the same source-destination pair are groomed into a lightpath lightpath request 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 by a lightpath request with SONET STS-192. These lightpath requests are served for wavelength assignment. The optical signals of the assigned wavelengths are sent by transmitters. Furthermore, 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.

(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 End-to-End Traffic Grooming

The aim of connection requests or bandwidth requests grooming is to enhance the effective utilization of a given capacity optical network. Before a connection request or bandwidth request is served, it can wait for a certain amount of time, say t_d. The t_d is the delay tolerance of a connection/bandwidth request, which is defined as a service-level specification to be stated in the SLA (Service Level Agreement). Since connection/bandwidth requests arrive at the system over a time period, the system waits for a certain amount of time. This waiting time, say min_{t_d} is the minimum delay tolerance of the connection/bandwidth requests. Within min_{t_d}, the connection/bandwidth requests having the same source-destination pair are groomed into a lightpath request with the SONET STS multiplexer, which is estimated by,

$$R = \left\{ r_1^{s,d}, r_2^{s,d}, \ldots, r_Z^{s,d} \right\} \mid \sum_{s,d} B(r_i^{s,d}) = B(L^{s,d}), \tag{4.1}$$

where R is the set of connection/bandwidth requests, which are groomed into a lightpath request. $B(r_i^{s,d})$ indicates the bandwidth requirement of connection/bandwidth request $r_i^{s,d}$ from source s to destination d. $B(L^{s,d})$ represents the bandwidth of lightpath request $L^{s,d}$ from source s to destination d, which accommodates connection/bandwidth requests having the same source-destination pair. Thereafter, the lightpath request is served for wavelength assignment. Note that, if a lightpath request is unable to wavelength assignment, all the connection/bandwidth requests that are groomed into the lightpath requests are considered as blocked.

4.5 Performance Analysis

This section presents simulation results of the end-to-end traffic grooming. The following assumptions are considered for the purpose of simulations. We consider NSFNET [1] and the Indian network [7] as network topologies, which are shown in Fig. 3.1 (p. 41) and Fig. 3.2 (p. 42), respectively. The connection/bandwidth requests are generated randomly based on a Poisson process and the holding time of connection/bandwidth requests follows an exponential distribution. The maximum

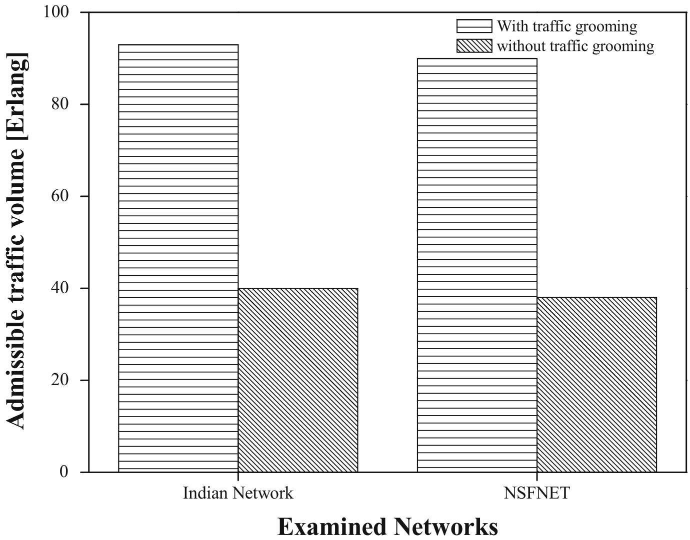

Fig. 4.2 Admissible traffic with and without incorporation of end-to-end grooming, when the blocking probability is considered 0.01

bandwidth requirement of a connection/bandwidth request is 622.08 Mbps according to SONET OC-12/STS-12, and the maximum capacity of each lightpath request is 9953.28 Mbps according to SONET OC-192/STS-192. We perform the simulation study of the end-to-end traffic grooming in terms of admissible traffic, and compare its result without incorporation of traffic grooming scenario. The routing is performed based on shortest path routing and the first fit [11, 12] policy is used for wavelength assignment purpose.

Figure 4.2 shows that the volume of admissible traffic using the first fit wavelength assignment policy with and without end-to-end grooming of connection/bandwidth requests for the Indian network and NSFNET, respectively, when the blocking probability is considered 0.01. The blocking probability is defined as a ratio of the number of blocked connection/bandwidth requests to the number of connection/bandwidth requests in the network. We observe that the admissible traffic with incorporation of grooming is higher than that of without grooming. When we do not consider grooming, each connection/bandwidth request is considered for wavelength assignment individually, which increases blocking in the network. When we consider grooming, the connection/bandwidth requests having the same source-destination pairs are groomed into a lightpath, which accommodates a large number of connection/bandwidth requests. This in turn accepts more admissible traffic in the network compared to without grooming. Furthermore, we perceive that the admissible traffic with incorporation of end-to-end traffic grooming in the Indian network is higher compared to NSFNET due to the effect of average node degree in the network. The average node degree in the Indian network is 3.43, which is greater than that of the average node degree (3) in NSFNET.

4.6 Conclusion

This chapter presented the end-to-end traffic grooming in order to avoid optical-electrical-optical conversions at each hop. The end-to-end traffic grooming multiplexes a number of low-speed connection/bandwidth requests that belong to same source-destination pair into a lightpath according to channel capacity. We observed that when the end-to-end traffic grooming is incorporated with routing and wavelength assignment approach, the admissible traffic volume adequately increases compared to non-traffic grooming scenario.

In the next three chapters, we will incorporate the end-to-end traffic grooming mechanism with RWA approaches for better utilization of network's resources.

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Chapter 5
Priority-Based Routing and Wavelength Assignment Scheme

5.1 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. In a without wavelength conversion capability network, wavelengths channels may be available but lightpath requests cannot be established due to the effect of wavelength continuity constant. In the absence of wavelength converters, the same wavelength must be used on all hops in the end-to-end path of a lightpath to satisfy the wavelength continuity constraint. To reduce the effect of the wavelength continuity constraint, several 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 [1–5]. Among these approaches, FF is considered to be one of the best in terms of call blocking, fairness and lower computational overhead.

To suppress the call blocking in the network, P. Rajalakshmi et al. [6, 7] presented wavelength reassignment algorithms using reconfiguration and minimum overlap techniques. In the reassignment technique, when a new call gets blocked due to wavelength continuity constraint, the already established calls or lightpaths are reassigned to the wavelengths in order to create a wavelength-continuous route. As a result, the new call is established. During wavelength reassignment, the routes for all the calls remain the same, and hence no rerouting is performed.

Recently, prioritization concepts have been incorporated with routing and wavelength assignment (RWA) approach for suppressing the call blocking in the network. Taking this direction, D.M. Shanan et al. [8, 9] presented a priority-based offline wavelength assignment scheme in optical burst switching networks without considering wavelength conversion. The key idea of the presented scheme is to decide the wavelength searching order of each traffic connection at edge nodes according to the

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wavelength priorities determined by the calculated burst loss probabilities on different wavelengths. However, they do not differentiate the connection requests and treat them the same way for RWA. As a result, the presented prioritization approach [8] could not improve the performance of the network beyond a certain limit.

This chapter explores the possibility of prioritizing connection requests to improve the network performance. Accordingly, lightpath requests are differentiated into different priority groups based on types of path and volume of traffic for improving the performance. This chapter introduces a priority-based routing and wavelength assignment (PRWA) scheme [10–12] to reduce the call blocking in the network. The results of the introduced PRWA scheme are compared with the conventional non priority-based routing and wavelength assignment (NPRWA) scheme.

The rest of this chapter is organized as follows. Section 5.2 describes the model, assumptions, and notations, which are used rest of this chapter. The introduced PRWA scheme is presented in Sect. 5.3. Further in that section, we elaborate the working principle of the PRWA scheme with the help of some examples. Section 5.4 evaluates the performance of the PRWA scheme under blocking and non-blocking conditions. Finally, Sect. 5.5 concludes this chapter.

5.2 Model and Assumptions

We model the optical network as a connected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has an order set $\Lambda=\{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\}$ of wavelengths. The following assumptions are considered in our model.

- Each fiber link can carry an equal number of wavelengths, and the network is without wavelength conversion capabilities.
- Two lightpaths sharing at least one fiber link are allocated with different 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.
- The connection requests having the same source-destination pair are groomed into a lightpath request by the synchronous optical networking (SONET) synchronous transport signal (STS) multiplexer within lightpath capacity.

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

5.3 Priority-Based Routing and Wavelength Assignment Scheme

This section introduces the priority-based routing and wavelength assignment (PWRA) scheme [10], which is intended to reduce the call blocking in the network. In the PRWA scheme, there are mainly two steps involved in constructing the

Table 5.1 Used notations and symbols

Notations/Symbols	Comments
G	Graph representation of the optical network
V	Set of nodes, where $V = \{v_1, v_2, \ldots, v_{\|V\|}\}$
E	Set of links, where $E = \{e_1, e_2, \ldots, e_{\|E\|}\}$
Λ	Set of wavelengths of each fiber link, where $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{\|\Lambda\|}\}$
Z	Ordered set of lightpath requests according to priority order, where $Z = \{z_1, z_2, \ldots, z_{\|Z\|}\} = X + U$
L	Number of physical links between a source-destination pair
X	Number of lightpath requests in the network having direct physical link
U	Number of lightpath requests in the network having in-direct physical link
K	Number of routes for a lightpath request
LR_1	Ordered set of lightpath requests having direct physical link
LR_2	Ordered set of lightpath requests having in-direct physical link
$lr_{D,i}^{s_i,d_i}$	The i^{th} lightpath request in LR_1
$lr_{I,i}^{s_i,d_i}$	The i^{th} lightpath request in LR_2
$Vol(lr_{I,i}^{s_i,d_i})$	Volume of traffic for lightpath request of $lr_{I,i}^{s_i,d_i}$
$Vol(lr_{D,i}^{s_i,d_i})$	Volume of traffic for lightpath request of $lr_{D,i}^{s_i,d_i}$

complete framework, namely, (i) priority order estimation and (ii) RWA approach. The overall framework of this scheme is being depicted in Fig. 5.1.

Initially, lightpath requests are enqueued in the priority queue to estimate the priority order according to Algorithm 1. Finally, these lightpath requests are served for RWA purpose according to their priority order as per Algorithm 2. The details of two steps of the PWRA scheme are presented in the following subsections.

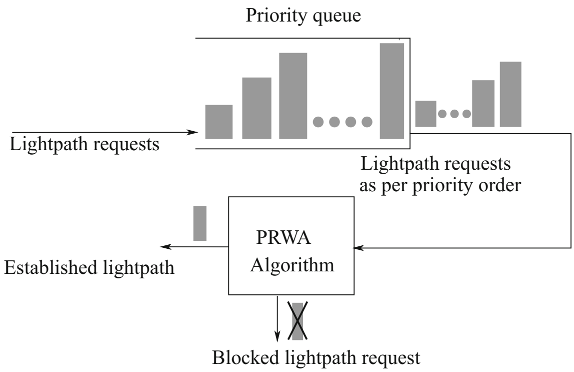

Fig. 5.1 Framework of PRWA scheme

Algorithm 1: Priority order estimation.

Input: Lightpath requests
Output: Estimation of priority order

1: Lightpath requests are enqueued into a priority queue.
2: Grouping lightpath requests into two categories, such as, direct physical link lightpath requests and in-direct physical link lightpath request.

$$LR_1 = \left\{ lr^{s_1,d_1}_{D,1}, lr^{s_2,d_2}_{D,2}, \ldots, lr^{s_X,d_X}_{D,X} \right\}$$
$$LR_2 = \left\{ lr^{s_1,d_1}_{I,1}, lr^{s_2,d_2}_{I,2}, \ldots, lr^{s_U,d_U}_{I,U} \right\}$$

such that

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

where LR_1 and LR_2 are the two ordered set of lightpath requests having direct and indirect physical link, respectively. The priority order of each lightpath request is assigned according to their positions either in GR_1 or in GR_2. Lightpath requests in LR_1 have higher priorities compared to lightpath requests in LR_2. $lr^{s_i,d_i}_{D,i}$ and $lr^{s_i,d_i}_{I,i}$ represent the i^{th} lightpath requests in LR_1 and LR_2, respectively. $Vol(lr^{s_i,d_i}_{D,i})$ and $Vol(lr^{s_i,d_i}_{I,i})$ indicate the volume of traffic for the lightpath request of $lr^{s_i,d_i}_{D,i}$ and $lr^{s_i,d_i}_{I,i}$, respectively.

5.3.1 Priority Order Estimation

The motivation of priority order estimation is to give preference to higher priority lightpath requests in order to maximize the number of established lightpaths. As a result, the call blocking in the network is drastically reduced. The priority order of each lightpath 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 lightpath requests are always given higher priority compared to lightpath requests having in-direct link. Furthermore, the lightpath requests with direct or in-direct link are arranged in the descending order of their traffic volume. In this work, we consider that the connection requests to be served by the PRWA approach have the same priority in terms of their quality-of-service (QoS) requirement. To achieve our goal, we consider type of paths and traffic volumes as the criteria for prioritizing of lightpath requests, which is required due to the wavelength continuity constraint in the network. 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 lightpath requests is estimated using these criteria, blocking of lightpath requests due to the effect 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. The estimation of priority order of lightpath requests is given in Algorithm 1. The overall time complexity of Algorithm 1 is O($|Z|\log|Z|$).

Example

To understand 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 six nodes and nine bi-directional optical links as depicted in Fig. 5.2. Each link has two wavelengths, such as, λ_1 and λ_2. We also assume five lightpath requests as shown in Table 5.2.

By applying Algorithm 1, two grouped order sets of lightpath requests (LR_1 and LR_2) are formed, such that $LR_1 = \{lr^{1,5}, lr^{1,6}, lr^{1,2}\}$ and $LR_2 = \{lr^{1,4}, lr^{1,3}\}$. Finally, the priority order of each lightpath request is estimated and shown in Table 5.3.

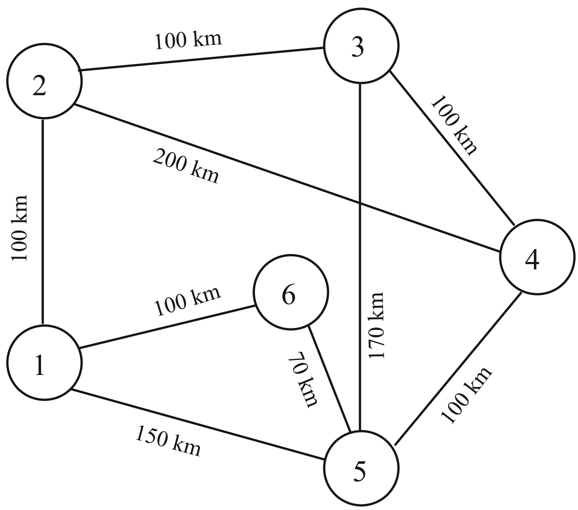

Fig. 5.2 Sample example network

Table 5.2 Lightpath requests with their traffic volume

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

Table 5.3 Lightpath requests with their priority

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

5.3.2 RWA Approach

The RWA approach is intended to select the best possible end-to-end routes and assign suitable wavelengths to lightpaths for serving lightpath requests. Here, an attempt is made to choose lightpath requests as per the priority order in order to reduce the effect of wavelength continuity constraint. The estimation of priority order for lightpath requests is already illustrated in Sect. 5.3.1. The details of RWA approach are given in Algorithm 2.

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

Input: lightpath requests according to their priority, LR_1 and LR_2 in priority queue (output from Algorithm 1)
Output: Wavelengths assignment

1: For each lightpath request, compute K number of shortest end-to-end paths on the basis of link state information.
2: For each lightpath request in LR_1 and LR_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.
(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), the lightpath request is treated as blocked one.
(d)Drop the lightpath request from the network.

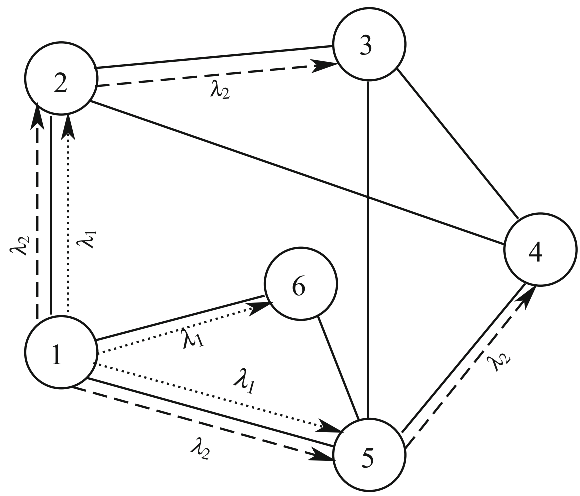

Fig. 5.3 Virtual topology of sample example network

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 number of the shortest paths for all lightpath requests is $O(((|E|+|V|\log|V|+K)\cdot|Z|))$ [13] or $O(((|V|(|V|-1)+|V|\log|V|+K)\cdot|Z|)) \equiv O((|V|^2\cdot|Z|))$.
- The order of time to perform wavelength assignment for Z number of lightpath requests using K alternate paths is $O(L\cdot|\Lambda|\cdot K\cdot Z)$ or $O((|V|-1)\cdot|\Lambda|\cdot K\cdot|Z|) \equiv O(|V|\cdot|Z|)$.

In the above steps, the first step is the dominating factor. Therefore, the overall time complexity of Algorithm 1 is $\equiv O((|V|^2\cdot|Z|))$.

Example

The functionality of Algorithm 2 is explained with the help of the same example as already discussed in Sect. 5.3.1. The lightpath requests in LR_1 and LR_2 are severed for RWA approach according to their priority order as shown in Table 5.3. Finally, the virtual topology of the sample network is formed and depicted in Fig. 5.3.

5.4 Performance Analysis

This section presents simulation results of the introduced PRWA scheme. The following assumptions are considered for the purpose of simulations. We consider NSFNET [1] and the Indian network [10] as network topologies, which are shown in Fig. 3.1 (p. 41) and Fig. 3.2 (p. 42), respectively. The lightpath requests are generated randomly based on a Poisson process and the holding time of lightpath requests follows an exponential distribution. We perform the simulation study of the PRWA scheme under blocking and non-blocking conditions of the network. The results of the PRWA scheme are compared with the conventional NPRWA scheme. The wavelength assignment is performed based on the FF method [3].

5.4.1 Blocking Case

This subsection evaluates the performance of the PRWA scheme in terms of blocking probability, which is defined as a ratio of the number of blocked lightpath requests to the number of lightpath requests in the network.

Figures 5.4 and 5.5 show blocking probability versus number of wavelengths, obtained by using the PRWA scheme in the Indian network and NSFNET, respectively, when 20 Erlang traffic load is considered. In both the figures, $K = 1$ corresponds to a primary route and other values of K (i.e. $K > 1$) represent using $K - 1$ number of alternate routes. It is 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 routes. The variation of blocking probability with number of wavelengths, using up to three (i.e. $K = 4$) alternate routes is close to that of using up to two (i.e. $K = 3$) alternate routes in the

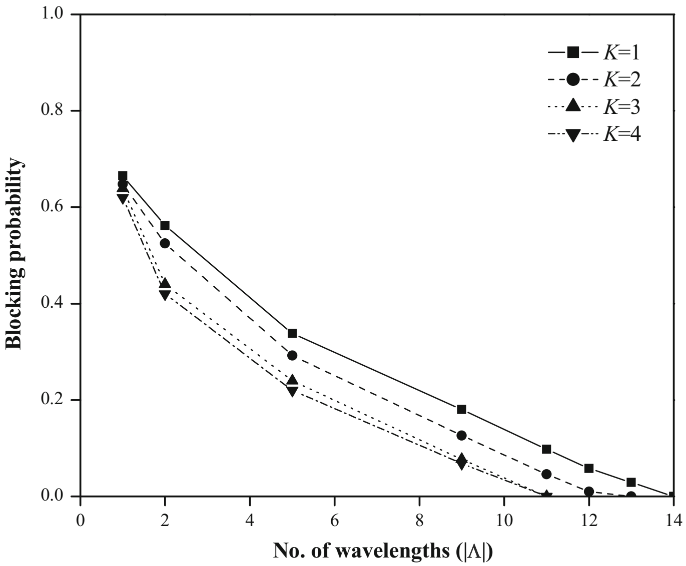

Fig. 5.4 Blocking probability versus $|\Lambda|$, obtained by using PRWA scheme in Indian network

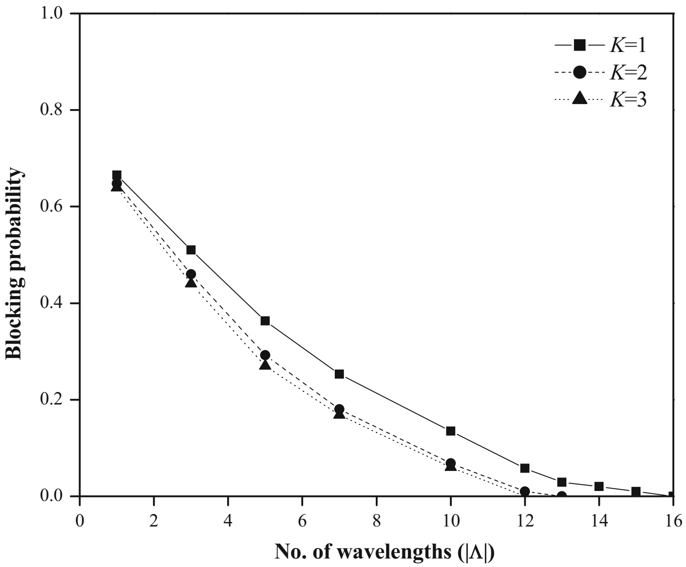

Fig. 5.5 Blocking probability versus $|\Lambda|$, obtained by using PRWA scheme in NSFNET

Indian network. Similarly, in NSFNET, the variation of blocking probability using up to two (i.e. $K = 3$) alternate routes is close to that of using up to one (i.e. $K = 2$) alternate route. We observed from Fig. 3.5 (p. 44) and Fig. 3.6 (p. 44) in Chap. 3 that the average setup time increases with increase in number of alternate routes. From the above analysis, we summarize that as the number of alternate routes 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 routes 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 the PRWA scheme.

We study the blocking probability using both the PRWA and NPRWA schemes with different traffic load in the Indian network and NSFNET as depicted in Figs. 5.6 and 5.7, respectively. It is observed from the figures that the blocking probability using the PRWA scheme is less than that of using the NPRWA scheme. This is because of incorporation of prioritization concept in the PRWA scheme. It is evident from Figs. 5.6 and 5.7 that the blocking probability increases with increase in traffic load. Furthermore, it is observed 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 routes in the Indian network compared to NSFNET.

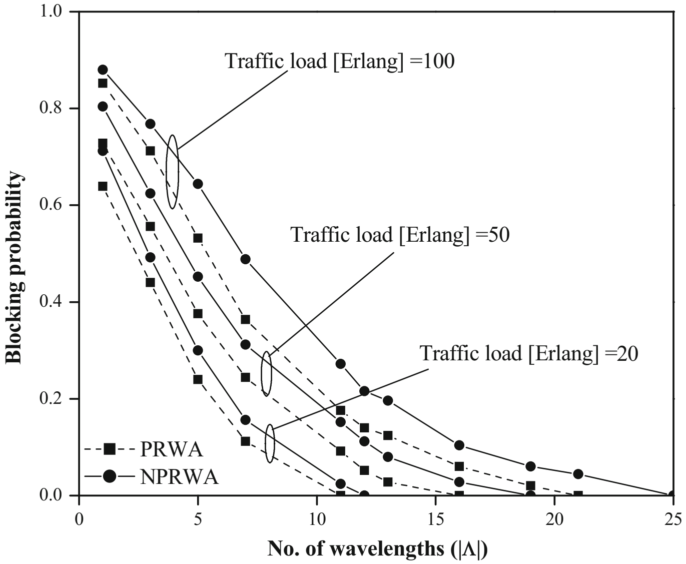

Fig. 5.6 Blocking probability versus $|\Lambda|$, obtained by using PRWA and NPRWA schemes, with different traffic load in Indian network

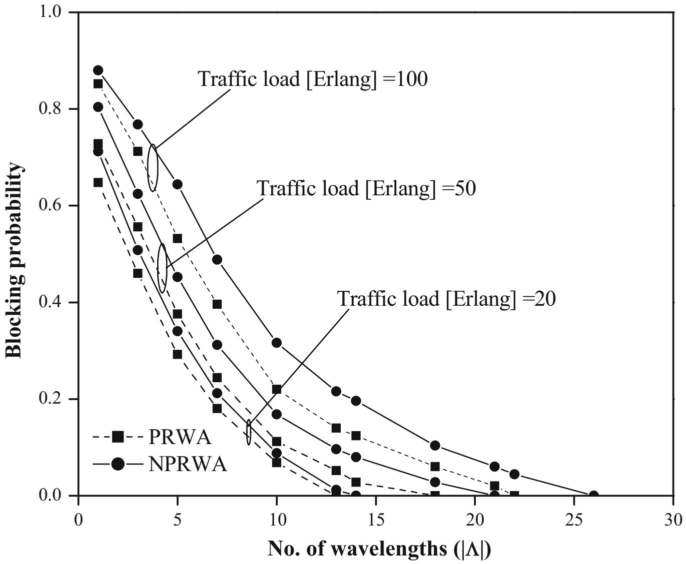

Fig. 5.7 Blocking probability versus $|\Lambda|$, obtained by using PRWA and NPRWA schemes, with different traffic load in NSFNET

5.4.2 Non-blocking Case

This subsection evaluates the performance of the PRWA scheme in terms of number of required wavelengths to achieve the non-blocking condition in the network. The situation where all the lightpath requests are successfully assigned is defined as the non-blocking condition.

Figures 5.8 and 5.9 depict the number of wavelengths versus traffic load, 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 accommodate 20 Erlang, 60 Erlang, and 100 Erlang volume of traffic using the PRWA scheme. To accommodate 20 Erlang, 60 Erlang, and 100 Erlang volume of traffic in the Indian network using the NPRWA scheme 12, 19 and 25 numbers of wavelengths are required, respectively. Similarly, it is observed from NSFNET that 14, 21 and 26 numbers of wavelengths are required to accommodate 20 Erlang, 60 Erlang, and 100 Erlang volume of traffic using the NPRWA scheme. However, 13, 18 and 22 numbers of wavelengths are required to accommodate the same volume of traffic in NSFNET using the PRWA scheme. We observe from Figs. 5.8 and 5.9 that as traffic volume increases, the rate of increase in number of wavelengths using the PRWA scheme is less than that of using the NPRWA scheme. The similar type of results is obtained in NSFNET as depicted in Fig. 5.9. However, the required number of wavelengths under non-blocking condition in NSFNET is slightly higher than that in the Indian network due to consideration

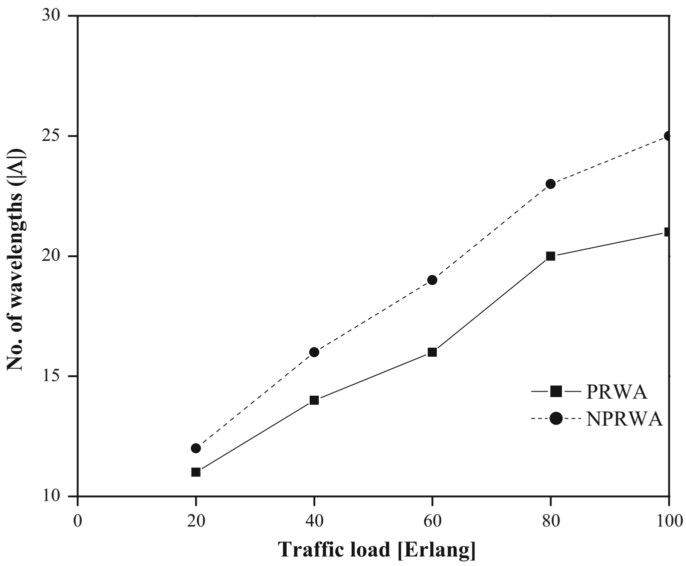

Fig. 5.8 $|\Lambda|$ versus traffic load, obtained by using PRWA and NPRWA schemes in Indian network

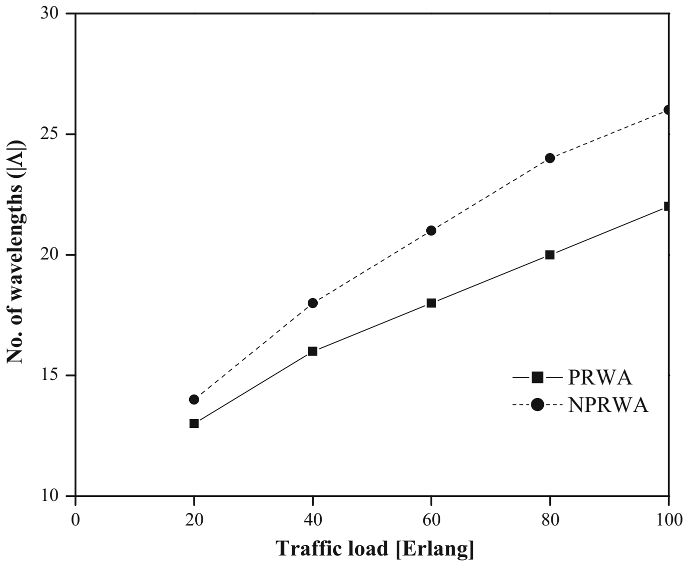

Fig. 5.9 $|\Lambda|$ versus traffic load, obtained by using PRWA and NPRWA schemes in NSFNET

of more number of alternate paths. From the analysis of Figs. 5.8 and 5.9, it is summarized that the PRWA scheme outperforms the NPRWA scheme as the volume of traffic increases in the networks.

5.5 Conclusion

This chapter introduced a priority-based routing and wavelength assignment (PRWA) scheme to suppress call blocking in the network. The introduced scheme serves lightpath requests according to their priority order. The priority order of lightpath request is estimated based on the types of path (direct link physical path or indirect link physical path) and the volume of traffic. The simulation results indicated that the blocking probability using the PRWA scheme is less than that of using the NPRWA scheme. Furthermore, we observed that the number of required wavelengths to achieve nonblocking condition in the network is reduced by the PRWA scheme.

Till now we have investigated the RWA problem for reducing the call blocking. Quality of service (QoS) is one of the critical design issues in wavelength division multiplexing (WDM) based optical network to maintain the signal quality, which will be addressed in the next chapter.

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Chapter 6
Priority-Based Dispersion-Reduced Wavelength Assignment Scheme

6.1 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, such as dispersion compensating fiber (DCF), optical phase conjugation, pulse prechirping and duobinary transmission, have been usually used to reduce dispersion effect, they require additional costs. 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 [1–4], are lacking of capability to take care of the reduction of overall dispersion in the network.

In this direction, N. Zulkifli et al. [5] presented a dispersion optimized impairment constraint (DOIC) based routing and wavelength assignment (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 requires an additional cost and its propagation loss is very high compared to step-index Fiber (SIF).

This chapter introduces a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme [6–8] in order to improve the overall signal quality in the network without using any dispersion compensating device. The introduced PDRWA scheme assigns longer lightpath requests to the wavelengths having lesser dispersion and the wavelengths having higher dispersion are assigned to the lightpaths with shorter distance.

B.C. Chatterjee et al., *Routing and Wavelength Assignment for WDM-based Optical Networks*, Lecture Notes in Electrical Engineering 410, DOI 10.1007/978-3-319-46203-5_6

The rest of this chapter is organized as follows. Section 6.2 describes the model, assumptions, and notations, which are used rest of this chapter. Section 6.3 describes the system and objective of this work. Section 6.4 presents the PDRWA scheme. Furthermore in that section, we elaborate the working principle of PDRWA scheme with the help of an example. Section 6.5 evaluates the performance of the introduced scheme under blocking and non-blocking conditions. Finally, Sect. 6.6 concludes this chapter.

6.2 Model and Assumptions

We model the optical network as a connected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has an order set $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\}$ of wavelengths. The following assumptions are considered in our model.

- Each fiber link can carry an equal number of wavelengths, and the network is without wavelength conversion capabilities.
- Two lightpaths sharing at least one fiber link are allocated with different 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.
- The connection requests having the same source-destination pair are groomed into a lightpath request by the synchronous optical networking (SONET) synchronous transport signal (STS) multiplexer within lightpath capacity.

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
G	Graph representation of the optical network
V	Set of nodes, where $V = \{v_1, v_2, \ldots, v_{\lvert V\rvert}\}$
E	Set of links, where $E = \{e_1, e_2, \ldots, e_{\lvert E\rvert}\}$
Λ	Set of wavelengths of each fiber link, where $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{\lvert\Lambda\rvert}\}$
Z	Ordered set of lightpath requests according to priority order, where $Z = \{z_1, z_2, \ldots, z_{\lvert Z\rvert}\}$
Λ'	Ordered set of wavelengths per fiber link in the increasing order of their dispersion
L	Number of physical links between a source-destination pair
K	Number of routes for a lightpath request
$D(\lambda)$	Coefficient of total dispersion in ps/(nm · km) of a wavelength

(continued)

Table 6.1 (continued)

Notations/Symbols	Comments
$D_m(\lambda)$	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
B	Channel bit rate
t_w	Source spectral line-width in nm
FL	Fiber length in kilometer

6.3 System Description

This section presents the estimation of total dispersion in the network considering the channel speed. Dispersion [9] 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 [10] 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 (≥10 Gbps) is given in Sect. 6.5.1. The amount of total dispersion in optical fiber can be represented as given in Eq. (6.1).

$$|D(\lambda)| = |D_m(\lambda)| + |D_{wd}(\lambda)|, \tag{6.1}$$

where

$$D_m(\lambda) = \frac{\lambda}{c} \cdot \frac{d^2(n_1)}{d\lambda^2} \tag{6.2}$$

$$D_{wd}(\lambda) = -\frac{2(n_1 - n_2)u^2}{c\lambda v^2}\left(1 - \frac{\lambda}{n_2} \cdot \frac{d(n_2)}{d\lambda}\right) \tag{6.3}$$

$$a'^2 = \frac{\lambda^2 v^2}{4\pi^2\left(n_1^2 - \beta^2\right)} \tag{6.4}$$

$$u^2 = a'^2\left(\frac{4\pi^2}{\lambda^2} \cdot n_1^2 - \beta^2\right) \tag{6.5}$$

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

$$n_j = \sqrt{1 + \sum_{i=1}^{3} \frac{b_i \lambda^2}{\lambda^2 - a_i^2}} \tag{6.6}$$

$$\frac{d(n_j)}{d\lambda} = -\frac{\lambda}{n_j}\sum_{i=1}^{3} \frac{a_i^2 b_i}{(\lambda^2 - a_i^2)^2} \tag{6.7}$$

$$\frac{d^2(n_j)}{d\lambda^2} = -\sum_{i=1}^{3} \frac{a_i^2 b_i}{(\lambda^2 - a_i^2)^2 \cdot n_j}\left[\frac{(a_i^2 + 3\lambda^2)}{(\lambda^2 - a_i^2)} + \frac{\lambda^2 \sum_{i=1}^{3} \frac{a_i^2 b_i}{(\lambda^2 - a_i^2)^2}}{(n_j)^2}\right] \tag{6.8}$$

We observe from the literature [11] that the dispersion increases with increase in channel bit rate. Therefore, we formulate 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. Note that $|N_D|$ indicates the amplitude of dispersion. The value of total dispersion is given in Eq. (6.9).

$$|N_D| = \sum_{i=1}^{|Z|} B \cdot \sum_{x,y} P^i_{x,y} \cdot D(\lambda) \cdot t_w \cdot (d_{x,y} \ mod \ A_s) \tag{6.9}$$

In Eq. (6.9), the total dispersion in the network is computed for all lightpath requests. We use a lightpath-link-indicator for each lightpath request, which is represented by $P^i_{x,y}$.

6.4 Priority-Based Dispersion-Reduced Wavelength Assignment Scheme

The introduced priority-based dispersion-reduced wavelength assignment scheme [6] is intended to reduce the total dispersion in the network without using any dispersion compensating device. The introduced scheme assigns the longer distance lightpath requests to the wavelengths having lower dispersion effect, and the wavelengths having higher dispersion effect are allocated to the shorter distance lightpath requests. In this scheme, the lightpath requests are served for wavelength assignment according to their priority order. The priority orders of all lightpath requests are estimated as per descending order of their primary lightpath lengths. Using this criterion, longer lightpath requests are always given higher priority compared to lightpath requests having shorter 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 lightpath requests of higher priority (longer lightpath) are assigned the wavelengths having lesser dispersion and the wavelengths having a higher dispersion are assigned to the lightpath requests with shorter distance. Use of a conventional wavelength assignment approach may lead to a situation where lightpath requests with longer distance are assigned the wavelengths having a higher dispersion and the wavelengths having lesser dispersion are assigned to the lightpath requests with shorter distance. As a result, the overall dispersion in the network may increases, which degrades the signal quality. Therefore, if the priority order of lightpath 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.

Time complexity analysis of Algorithm 3

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

- The order of time to compute K number of the shortest paths for all lightpath requests and sort them in descending order of their primary path lengths is $\mathrm{O}(((|E|+|V|\log|V|+K)\cdot|Z|)+|Z|\log|Z|)$ [12] or $\mathrm{O}(((|V|(|V|-1)+|V|\log|V|+K)\cdot|Z|)+|Z|\log|Z|) \equiv \mathrm{O}((|V|^2\cdot|Z|)+|Z|\log|Z|)$.
- The order of time to arrange all the wavelengths in the network according to increasing order of their dispersion is $\mathrm{O}((|\Lambda|\log|\Lambda|)\cdot|E|)$ or $\mathrm{O}((|\Lambda|\log|\Lambda|)\cdot|V|(|V|-1)) \equiv \mathrm{O}(|V|^2)$.
- The order of time to perform wavelength assignment for Z number of lightpath requests using K alternate paths is $\mathrm{O}(L\cdot|\Lambda|\cdot K\cdot Z)$ or $\mathrm{O}((|V|-1)\cdot|\Lambda|\cdot K\cdot|Z|) \equiv \mathrm{O}(|V|\cdot|Z|)$.

In the above steps, the first step is the dominating factor. Therefore, the overall time complexity of Algorithm 3 is $\equiv \mathrm{O}((|V|^2\cdot|Z|)+|Z|\log|Z|)$.

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

Input: Lightpath requests
Output: Wavelengths assignment and total dispersion of the network

1: For each lightpath 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.

$$Z = \{z_1, z_2, \ldots, z_{|Z|}\} \mid \mathrm{dis}(z_1) \geq \mathrm{dis}(z_2) \geq \cdots \geq \mathrm{dis}(z_{|Z|}),$$

where Z is the ordered set of lightpath requests and the priority orders of lightpath requests are assigned according to their positions in Z. $\mathrm{dis}(z_i)$ indicates the length of primary lightpath of a lightpath request.

2: Arrange the wavelengths of each fiber link in the increasing order of their dispersion, estimated using Eqs. (6.1)–(6.8).

$$\Lambda' = \{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\} \,|D(\lambda_1) \leq D(\lambda_2) \leq \cdots \leq D(\lambda_{|\Lambda|}),$$

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

3: For each of the lightpath request in Z, 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 3(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 3(a)) till one alternate path is assigned a wavelength.

(c) If no wavelength assignment is possible either in step 3(a) or step 3(b), the lightpath request is treated as blocked one. Otherwise, compute the dispersion (with the assigned wavelength) for the lightpath request and add this dispersion to the total dispersion in the network.

(d) Drop the lightpath request from the network.

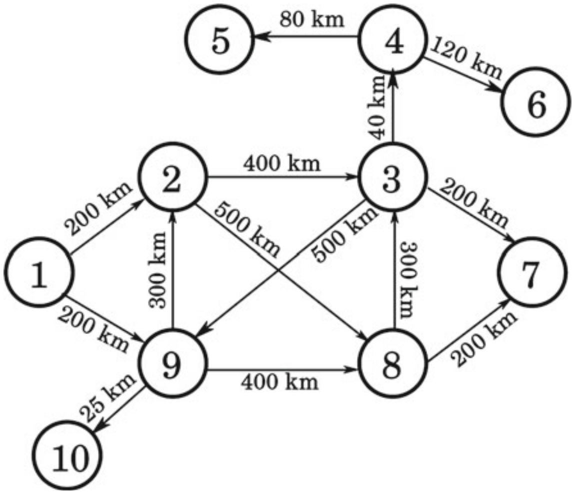


Fig. 6.1 Physical topology of sample network

Example

To understand the functionality of the PDRWA algorithm, we explain it with the help of a sample example network as shown in Fig. 6.1. It consists of 10 nodes, 13 directed optical links and each link has three available wavelengths, 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. The shortest distance of a lightpath request from source node 1 to destination node 6 is 760 km, which is considered as a longer lightpath request. If the wavelength assignment of the lightpath request is performed based on the conventional FF [1] policy, the lightpath request is assigned with λ_1, and the dispersion of the lightpath is 15200 ps/nm. However, if the wavelength assignment of the lightpath request is performed using the PDRWA algorithm, the lightpath request is assigned with λ_2 and the dispersion of the lightpath is 13680 ps/nm.

6.5 Performance Analysis

This section presents simulation results of the introduced PDRWA scheme. The following assumptions are considered for the purpose of simulations. We consider NSFNET [1] and the Indian network [13] as network topologies, which are shown in Figs. 3.1 and 3.2, respectively. The lightpath requests are generated randomly based on a Poisson process and the holding time of lightpath requests follows an exponential distribution. Measurements can be performed on materials contemplated for core GeO_2:86.5 SiO_2 compositions and for claddings Quenched SiO_2, respectively, [14] as shown in Table 6.2. The wavelength range is considered from 1.520–1.590 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 [15]. As the

Table 6.2 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 6.3 System parameters and their values in our models

Parameter	Value
EXTP	20 dB [16]
Δf_{opt}	100 GH_z
σ_λ	70 nm
NF	5 dB [17]
σ_0	50 ps [18]
Average span loss in SIF	23 dB [19]
Average span loss in DCF	13 dB [20]
EDFA interval in SIF	100 km [21]
EDFA interval in DCF	15 km [21]
Propagation loss in SIF	0.2 dB/km [22]
Propagation loss in DCF	0.6 dB/km [22]
D_{PMD} for SIF	0.05 ps/$\sqrt{\text{km}}$ [17]
D_{PMD} for DCF	0.1 ps/$\sqrt{\text{km}}$ [23]

quality of the signal (Q-factor) varies with channel speed, we consider wavelength channels having three different capacities, such as, 10 Gbps (OC-192/STS-192), 40 Gbps (OC-768/STS-768) and 100 Gbps, respectively. The used system parameters are summarized in Table 6.3.

The results of the PDRWA scheme are compared with a similar type of non dispersion-reduced wavelength assignment (NDRWA) scheme, where wavelength assignment is performed based on existing FF method [3]. For our simulation study, we estimate the dispersion of SIF using Eqs. (6.1)–(6.8), as shown in Fig. 6.2. In this figure, we incorporate the experimental results of dispersion in DCF developed by PureGuide® [24]. It is observed from Fig. 6.2 that the dispersion using SIF increases with increase in wavelength, but it is almost constant for DCF. Although, it can be found from Fig. 6.2 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 (see Fig. 6.3). Therefore, we use SIF with the PDRWA scheme and compare the same with DCF.

Figures 6.4 and 6.5 show the dependence of dispersion and the number of required wavelengths on the number of paths, obtained by using PDRWA in the Indian network and NSFNET, respectively. For this simulation study, 10 Erlang of traffic load and 10 Gbps channel speed are considered. In both the figures, $K = 1$ corresponds to a primary route and other values of K (*i.e.* $K > 1$) represent using K-1 number of alternate routes. It is evident from both the networks that the number of wavelengths

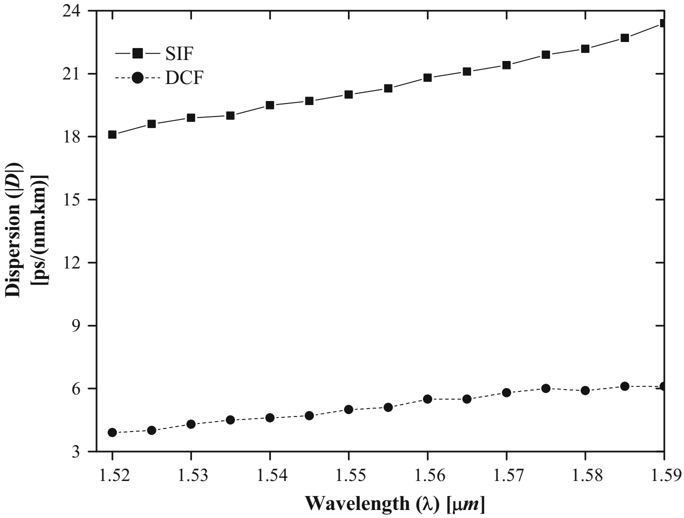


Fig. 6.2 Dispersion versus wavelength for SIF and DCF

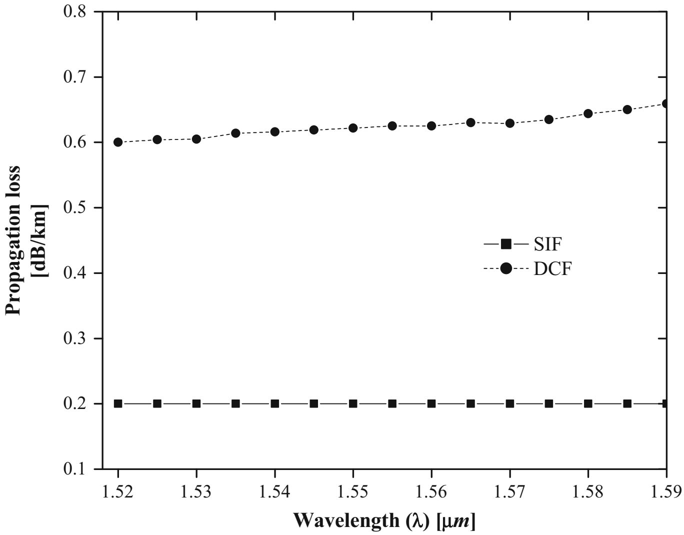


Fig. 6.3 Propagation loss versus wavelength for SIF and DCF

decreases with increase in number of routes. This is because more routes are used to establish lightpath requests successfully. We observe that as the number of routes increases, total dispersion increases due to increase in lightpath length. The number of required wavelengths and total dispersion of the network cross each other, when the number of routes (*i.e. K* value) is considered up to two and three for NSFNET

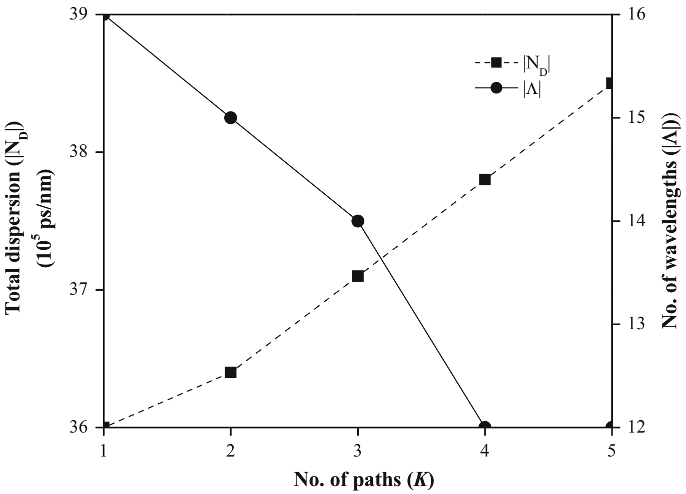


Fig. 6.4 Dependence of $|N_D|$ and $|\Lambda|$ on K, obtained by using PDRWA scheme in Indian network with 10 Gbps channel speed

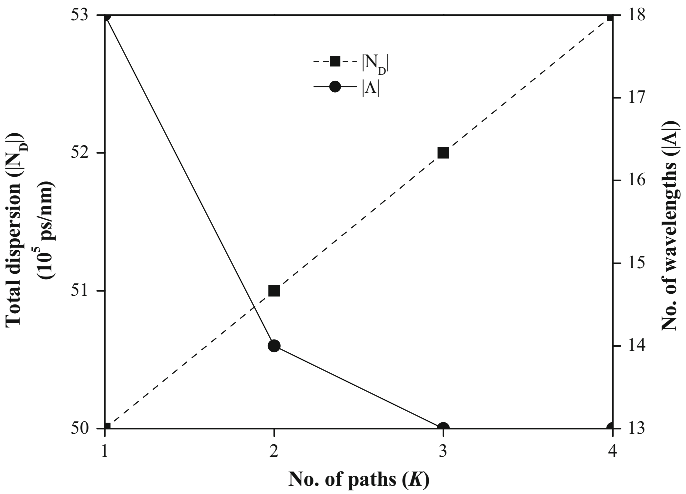


Fig. 6.5 Dependence of $|N_D|$ and $|\Lambda|$ on K, obtained by using PDRWA scheme in NSFNET with 10 Gbps channel speed

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 noticed in Figs. 3.5 and 3.6 of Chap. 3 that the average setup time increases with increase in number of routes. Furthermore, we observe that for higher bit rate channel, like −40 and 100 Gbps, K values remain almost the same. Therefore, the number of alternate routes 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 the PDRWA scheme.

6.5.1 Non-blocking Case

This subsection evaluate the performance of the PDRWA scheme in terms of total dispersion and total propagation loss in the network under non-blocking condition. The results are compared with the NDRWA scheme for different channel speeds.

Figures 6.6 and 6.7 show total dispersion versus traffic load, obtained by using PDRWA and NDRWA schemes respectively in the Indian network and NSFNET with different channel 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 the PDRWA scheme is less than that of using the NDRWA scheme. This is because in the PDRWA scheme, lightpath requests with longer distance are assigned to the wavelengths having lesser dispersion and vice versa. Furthermore, it is observed from both Figs. 6.6 and 6.7 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.

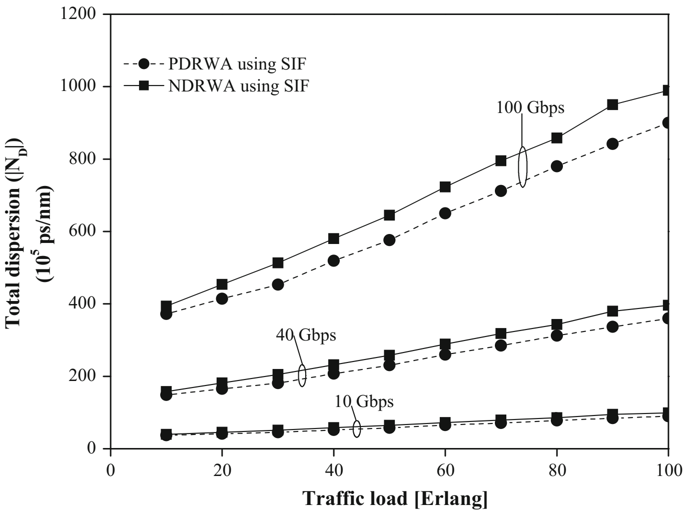


Fig. 6.6 $|N_D|$ versus traffic load, obtained by using PDRWA and NDRWA schemes in Indian network with different channel speeds

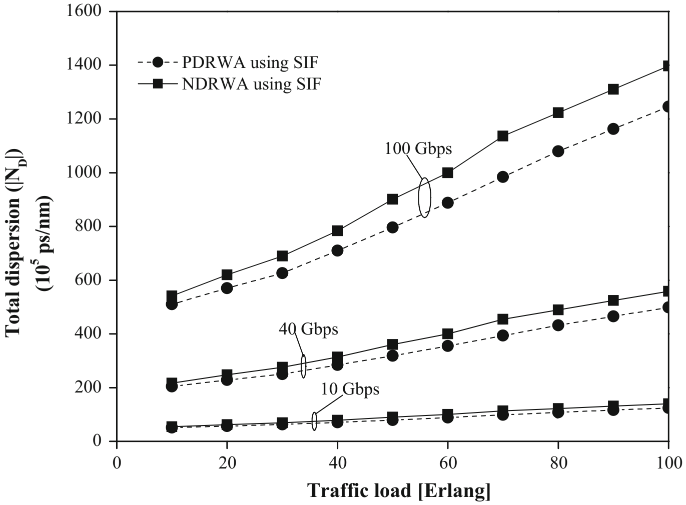
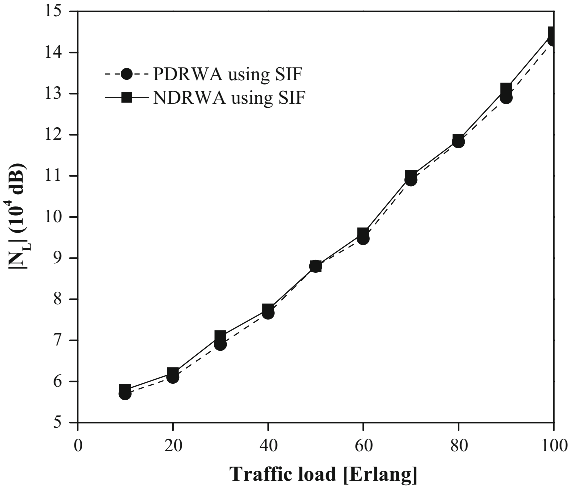


Fig. 6.7 $|N_D|$ versus traffic load, obtained by using PDRWA and NDRWA schemes in NSFNET with different channel speeds

Fig. 6.8 $|N_L|$ versus traffic load, obtained by using PDRWA and NDRWA schemes in Indian network with 10 Gbps channel speed



Total propagation loss versus traffic load with 10 Gbps channel speed in the Indian network and NSFNET are depicted in Figs. 6.8 and 6.9, respectively. It is evident in both networks that the variation of total propagation loss with traffic load using the PDRWA scheme is almost close to that of using the NDRWA scheme. From the above analysis, we can summarize that the total dispersion significantly reduces by using the PDRWA scheme without increasing total propagation loss in the network irrespective of channel speeds.

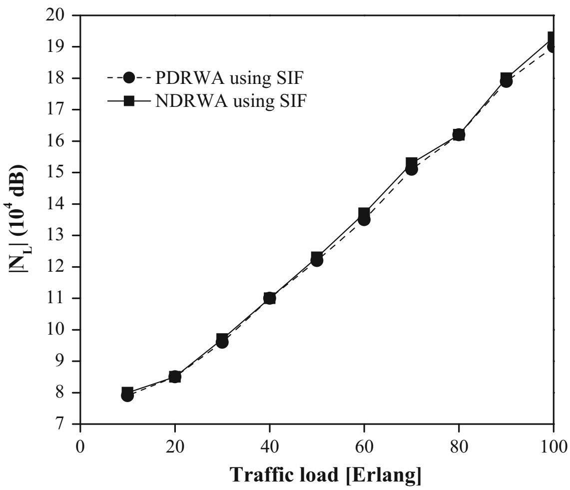


Fig. 6.9 $|N_L|$ versus traffic load, obtained by using PDRWA and NDRWA schemes in NSFNET with 10 Gbps channel speed

Furthermore, it has been reported [10] in the literature that for higher bit rate channel ($\geq$10 Gbps), the pulse-broadening effect caused by polarization mode dispersion (PMD) degrades the signal quality. Therefore, we study PMD effect in the PDRWA scheme with the use of SIF and DCF. The PMD [10, 11, 17] in a path with M hops is estimated as given in Eq. (6.10). The symbols used in this equation are given in Table 6.1.

$$PMD_{path} = B\sqrt{\sum_{j=1}^{M} D_{PMD}^{2} \cdot d_j} \tag{6.10}$$

Figure 6.10 shows the total PMD versus traffic load, 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 traffic load 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 [23]. It can be observed from Fig. 6.10 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.

6.5.2 Blocking Case

This subsection evaluates the performance of the PDRWA scheme in terms of blocking probability, which is defined as a ratio of the number of blocked lightpath requests to the number of lightpath requests in the network. Note that the blocking of lightpath

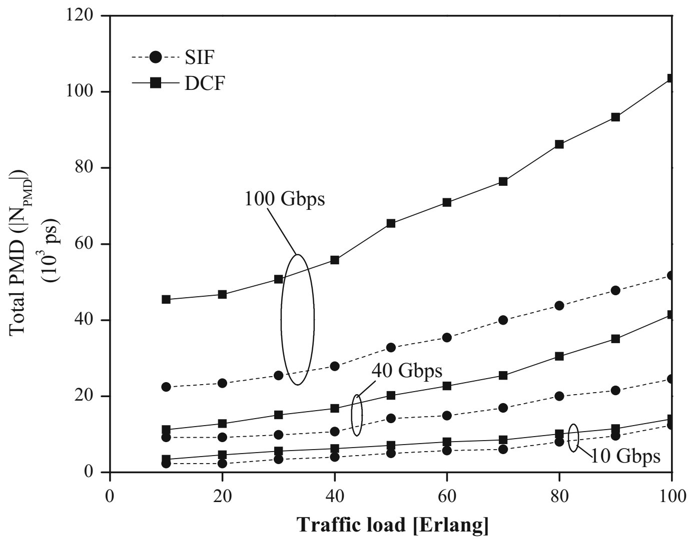


Fig. 6.10 $|N_{PMD}|$ versus traffic load for SIF and DCF with different channel speeds (10, 40 and 100 Gbps) in Indian network under non-blocking condition

requests is considered due to unavailability of required wavelengths; in this simulation, we do not block any lightpath request due to dissatisfiedness of signal quality threshold level.

Figures 6.11 and 6.12 show the blocking probability versus total number of wavelengths, obtained by using PDRWA and NDRWA schemes in the Indian network and NSFNET, respectively, with 10 Erlang traffic load 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 Figs. 6.11 and 6.12 that the blocking probability in the Indian network is less compared to NSFNET.

6.5.3 Q-Factor Analysis

As dispersion in optical fiber degrades the quality of signal, it is required to study the overall signal quality (Q-factor) in the network while applying the PDRWA scheme. The Q-factor of signal is given in Eqs. (6.11) and (6.12), respectively, for without PMD and with PMD cases as defined in [16, 19, 25]. The symbols used in the above equations are given in Table 6.1.

This subsection evaluates the performance of the PDRWA scheme in terms of overall signal quality (Q-factor) in the network. The results are compared with the

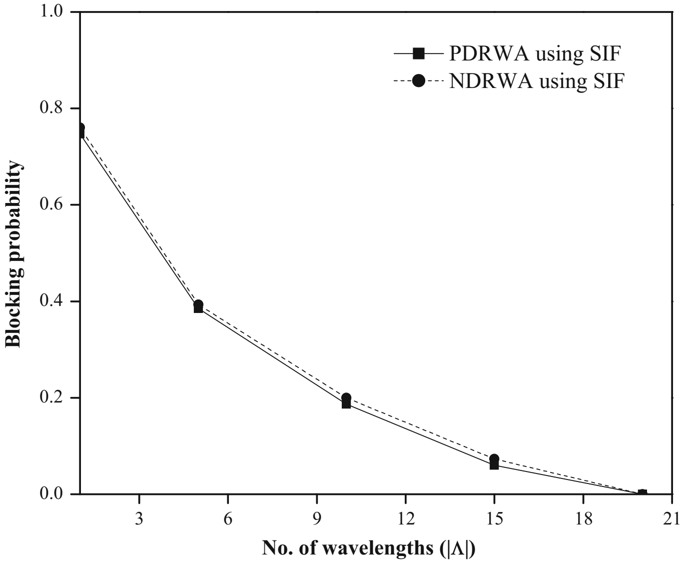


Fig. 6.11 Blocking probability versus $|\Lambda|$, obtained by using PDRWA and NDRWA schemes in Indian network with 10 Gbps channel speed

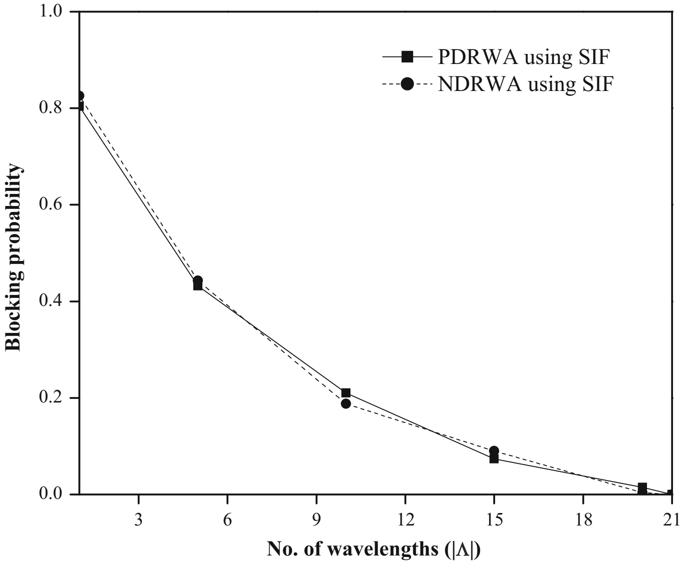


Fig. 6.12 Blocking probability versus $|\Lambda|$, obtained by using PDRWA and NDRWA schemes in NSFNET with 10 Gbps channel speed

NDRWA scheme with the use of SIF and DCF for varying traffic load and channel speeds.

$$Q_{\text{without PMD}} = \sqrt{\frac{OSNR}{EOP} \cdot \frac{\Delta f_{opt}}{\Delta f_{el}} \cdot EXTP} \tag{6.11}$$

$$Q_{\text{with PMD}} = \frac{Q_{\text{without PMD}}}{EOP_{PMD}}, \tag{6.12}$$

where

$$EOP = 10 \log \left(\sqrt{1 + \left(D(\lambda) F L' \frac{\sigma_\lambda}{\sigma_0} \right)^2} \right) \tag{6.13}$$

$$EOP_{PMD} = 5.1 \left(\frac{PMD_{path}}{T_B} \right)^2 \tag{6.14}$$

$$OSNR = P_{in} + 58 - P_s - NF - 10 \log_{10} N' \tag{6.15}$$

$$T_B = \frac{1}{B} \tag{6.16}$$

Figures 6.13 and 6.14 show the overall Q-factor versus traffic load, estimated by using PDRWA and NDRWA schemes in the Indian network and NSFNET, respectively. We estimate 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 are estimated without incorporation of PMD effect. It is evident from Figs. 6.13 and 6.14 that the Q-factor of the signal decreases with increase in traffic load. This is due to increase of total lightpath distance with increase in traffic load. In the figures, Q-factor using the NDRWA scheme with SIF is lower than that of using other schemes. The Q-factor using the PDRWA scheme with SIF increases due to assignment of less dispersion wavelength to the lightpath requests having longer paths and vice versa. Furthermore, it is observed from both Figs. 6.13 and 6.14 that Q-factor using the PDRWA scheme with DCF is almost close to that of using the 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 is found from the figures that the Q-factor using the PDRWA scheme with SIF is more than that of using the NDRWA scheme with DCF. We also notice from Figs. 6.13 and 6.14 that the Q-factor in NSFNET is less than that in the Indian network.

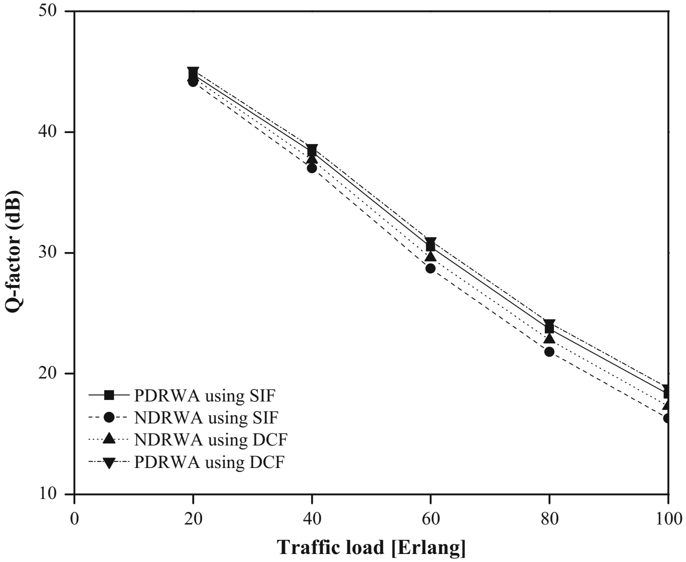


Fig. 6.13 Q-factor versus traffic load, obtained by using PDRWA and NDRWA schemes in Indian network without PMD effect and 10 Gbps speed

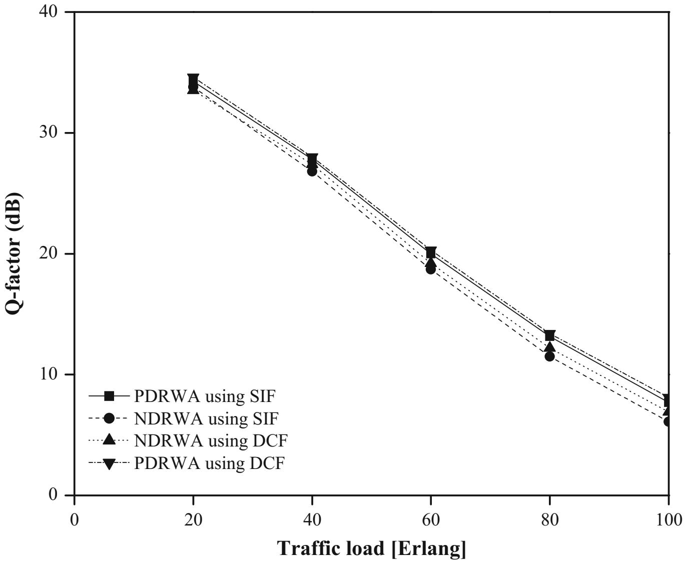


Fig. 6.14 Q-factor versus traffic load, obtained by using PDRWA and NDRWA schemes in NSFNET without PMD effect and 10 Gbps speed

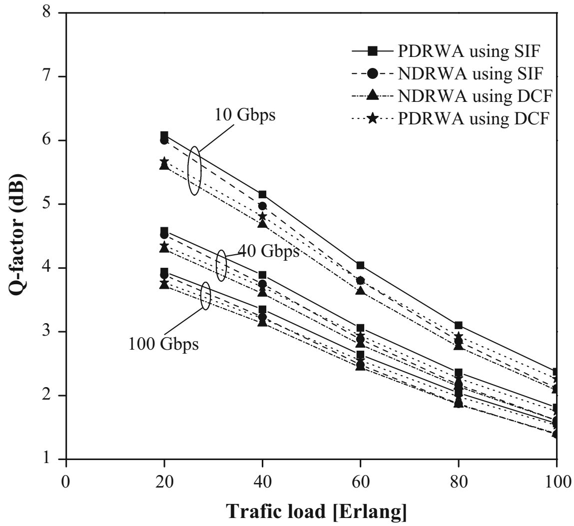


Fig. 6.15 Q-factor versus traffic load, obtained by using PDRWA and NDRWA schemes in Indian network (without PMD effect and 10 Gbps speed)

Considering channel data speed greater than or equal 10 Gbps, we study the overall Q-factor in the network with incorporation of PMD effect. Figure 6.15 depicts overall Q-factor versus traffic load, 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 are 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 observe in Fig. 6.13 that the Q-factor (without PMD effect) of signal using the PDRWA scheme with DCF is more than that of using other schemes. However, the overall Q-factor with PMD effect using the PDRWA scheme with SIF is more than that of using the PDRWA scheme with DCF. This is mainly due to higher PMD coefficient of DCF. Furthermore, it is found from Fig. 6.15 that in PDRWA scheme with SIF, the rate of decrease of Q-factor with traffic load is less than that of other schemes due to lesser power penalty of SIF.

6.6 Conclusion

This chapter introduced a priority-based dispersion-reduced wavelength assignment (PDRWA) scheme to reduce the overall dispersion in optical networks. The introduced scheme assigns the longer distance lightpath requests to the wavelengths having lower dispersion effect, and the wavelengths having higher dispersion effect are allocated to the shorter distance lightpath requests. The simulation results indicated that although, the dispersion with use of DCF is lower than that of the SIF, the propagation loss in DCF is three times higher than that of SIF. We observed that the total dispersion in the network significantly reduces using the PDRWA scheme with SIF, while maintaining the call blocking and without increasing total propagation loss in the network. Furthermore, we found that the total dispersion increases with channel speed but the rate of increase of total dispersion using the PDRWA scheme is less than that of using the NDRWA scheme. Finally, we observe that the Q-factor (with PMD effect) while using the PDRWA scheme with SIF is more than that of using the PDRWA scheme with DCF, due to the higher PMD coefficient.

Till now we investigated the RWA problem for suppressing the call blocking and improving the quality-of-service (QoS) in terms of Q-factor in optical networks. Nowadays, survivability against failures has become an important issue in wavelength division multiplexing (WDM) based optical networks due to increasing dependency on this network, which will be addressed in the next chapter.

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Chapter 7
A Reliable Fault Resilience Scheme

7.1 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). A single wavelength channel can nowadays carry a huge amount of information that is in the order of Tb/s range. Therefore, failure of a wavelength channel can disrupt communications for millions of users, which leads 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 [1]. Thus, the survivability [2–4] against the failures have become an important requirement in an optical network.

Taking this direction, researchers have demonstrated that protection [5–10] and restoration [3, 5–7, 9, 11] are the key strategies for handling failures in optical networks, and hence to improve the network reliability. In protection, backup resources (routes and wavelengths) are precomputed and reserved in advance prior to fault occurrence. On the other hand, restoration technique discovers backup resources (routes and wavelengths) dynamically on the basis of link-state information after the fault occurrence. It had been revealed that the recovery time of a protection technique is much smaller than that of a restoration scheme; the protection technique reserves backup resources prior to fault occurrence. Therefore, protection technique is more preferable for designing a faster recovery system.

Various protection techniques, such as network protection cycles [12–14] and ring covers [15, 16] have been presented in mesh optical networks to promote network robustness. However, determination of a protection ring or cycle path requires each

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network node to have knowledge of the entire network topology. As a result, any change in network topology demands a re-execution of the algorithm at every node. Disadvantageously, sometime processing of protection paths may include long distance nodes from the network node that has failed, which reduces network efficiency.

To overcome the problems of protection cycles and ring covers, researchers have focused on tree-based protection [8, 17–19]; it provides more flexibility and scalability. The main advantage of tree-based protection technique is easy to add or drop a branch, which have a limited impact on the other branches. This is as opposed to protection cycles and ring covers, which essentially lose their ring form if a single link on the ring is removed. Therefore, tree-based protection techniques are widely acceptable for dealing failures in optical mesh networks.

Till date, mainly two types of tree-based protection mechanism, namely (i) shared protection (1:M) [5, 10, 20] and (ii) dedicated protection (1:1) [5, 7] have been used by network operators and 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. Although dedicated protection technique provides more reliability, a huge number of wavelength channels are reserved in advance irrespective of the occurrence of a fault, which leads call blocking in the network. Therefore, recent research focuses on the shared protection technique in order to minimize the call blocking by utilizing the network resources. However, the shared protection technique is unable to provide the network reliability in a situation when simultaneous faults occur along the working paths.

The objective of this chapter is to circumvent the drawback of the shared protection technique by pursuing a reliable fault resilience scheme [21], which improves the reliability in the network. The introduced fault resilience scheme protects an established lightpath using the reliable protection tree. This protection tree is constructed by restricted sharing of a wavelength in the sub branch of the tree. In the reliable shared protection tree, if any two different end-to-end routes from the root node to leaf nodes have a common link, they do not share the same wavelength among themselves. However, the backup paths on the same end-to-end route share the same wavelength among themselves in order to save the resource usages. If any fault occurs in any wavelength, only backup paths associated with the wavelength are affected without influencing other backup paths. As a result, the reliability in the network is improved.

The rest of this chapter is organized as follows. Section 7.2 describes the model, assumptions, and notations, which are used rest of this chapter. The fault detection network architecture is presented in Sect. 7.3 along with the functionality of its components. Section 7.4 presents the reliable fault resilience scheme. We elaborate the working principle of the introduced scheme with the help of examples. Section 7.5 evaluates the performance of the introduced scheme. Finally, Sect. 7.6 concludes this chapter.

7.2 Model and Assumptions

We model the optical network as a connected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has an order set Λ=$\{\lambda_1, \lambda_2, \ldots, \lambda_{|\Lambda|}\}$ of wavelengths. The following assumptions are considered in our model.

- Each fiber link can carry an equal number of wavelengths, and the network is without wavelength conversion capabilities.
- Two lightpaths sharing at least one fiber link are allocated with different 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.
- The connection requests having the same source-destination pair are groomed into a lightpath request by the synchronous optical networking (SONET) synchronous transport signal (STS) multiplexer within lightpath capacity.
- Each optical amplifier and network node have a fault surveillance controller.
- The reliability of each component of working path is same.
- The reliability of each component of backup path is same.

For the remainder of this chapter, the symbols and notations used are summarized in Table 7.1.

7.3 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 [4, 11] to identify fault.

7.3.1 Link and Amplifier Fault Detection

Figure 7.1 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* and *OP* is controlled by a state machine belongs to the fault processing unit as shown in

Table 7.1 Used notations and symbols

Notations/Symbols	Comments
G	Graph representation of the optical network
V	Set of nodes, where $V = \{v_1, v_2, \ldots, v_{\|V\|}\}$
E	Set of links, where $E = \{e_1, e_2, \ldots, e_{\|E\|}\}$
Λ	Set of wavelengths of each fiber link, where $\Lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_{\|\Lambda\|}\}$
Z	number of lightpath requests
$N_R(t)$	Average reliability in the network
$R_i^{WP}(t)$	Reliability of component i for working path over a period of time t
$R_i^{BP}(t)$	Reliability of component i for backup path over a period of time t
$R_j(t)$	Probability that lightpath j does not fail over a period of time t
$R_j^{SP}(t)$	Reliability of lightpath j over a period of time t using the SP approach
$R_j^{RPTD}(t)$	Reliability of lightpath j over a period of time t using the RPTD approach
C_j^{WP}	Set of components that the working path of lightpath j uses
C_j^{BP}	Set of components that the backup path of lightpath j uses
C_j^{SP}	Set of components that the backup path of lightpath j uses in each hop using SP technique
C_j^{RPTD}	Set of components that the backup path of lightpath j uses in each hop using RPTD approach
H_j	Set of all hops contained by the lightpath j
$N_R^{SP}(t)$	Average reliability in the network over a period of time t using SP approach
$N_R^{RPTD}(t)$	Average reliability in the network over a period of time t using RPTD approach
f_{WP}	Failure rate of each component (say wavelength) of working path
f_{BP}	Failure rate of each component (say wavelength) of backup path

Fig. 7.2. 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.

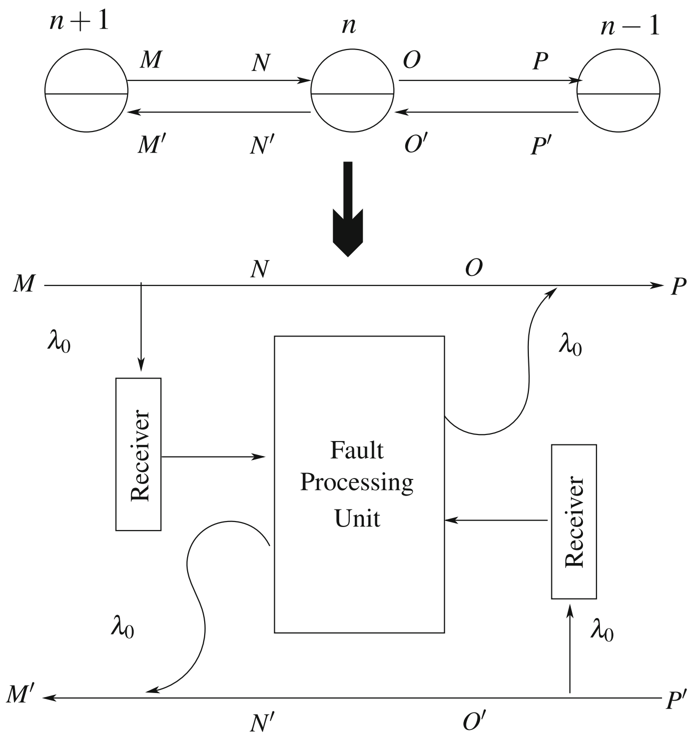

Fig. 7.1 Fault detection for link segments and optical amplifiers

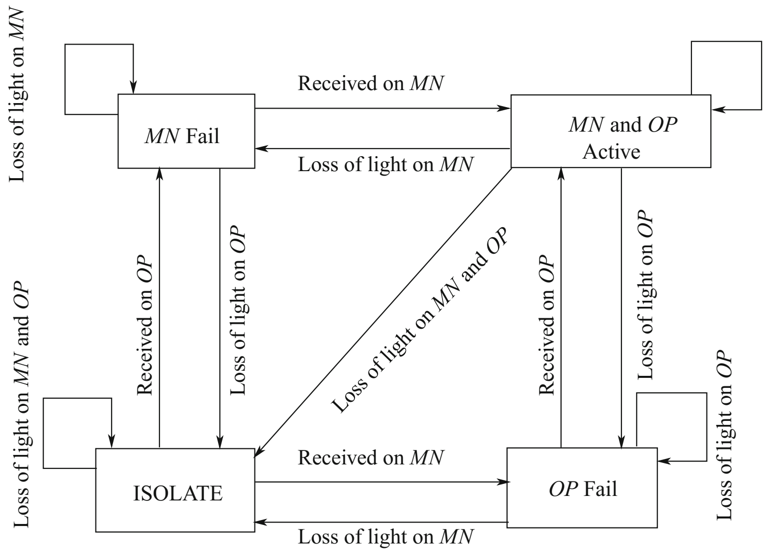

Fig. 7.2 Link and amplifier fault detection using finite-state machine

7.3.2 Node Fault Detection

Detecting a fault inside a network node is more difficult. 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.

7.4 Reliable Fault Resilience Scheme

This section presents the introduced reliable fault resilience scheme, which is intended to improve the average reliability in the network. If any fault occurs in a working path, the signal is switched to the backup path from the working path in order to continue the data transmission. The introduced scheme forms the backup path in advance according to our introduced reliable protection tree designing algorithm. The reliable protection tree is constructed by restricted sharing of a wavelength in the sub branch of the tree. In the reliable shared protection tree, if any two different end-to-end routes from the root node to leaf nodes have a common link, they do not share the same wavelength among themselves. However, the backup paths on the same end-to-end route share the same wavelength among themselves in order to save the resource usages, which suppresses the call blocking. The reliable protection trees are constructed for each source node to other nodes in the network. If a network has n nodes, the n number of reliable protection trees is required to protect all working paths in the network.

The conventional shared protection scheme shares a wavelength among all routes in a protection tree to provide the reliability in the network. If any fault occurs in a wavelength, all the backup paths in the sub branch are affected. However, the reliable protection tree provides more reliability as any two different end-to-end routes from the root node to leaf nodes sharing at least one link are allocated with different wavelengths. If any fault occurs in any wavelength, only backup paths associated with the wavelength are affected without influencing other backup paths. As a result, the reliability in the network is improved.

Algorithm 4 shows the procedure to create the reliable protection trees. The overall time complexity of this algorithm is expressed as $O(|V|+|E|)$. The functionality of this algorithm is explained with the help of a sample example network as shown in Fig. 7.3. We construct a breadth-first protection tree (BFPT) for the source node 1 as shown in Fig. 7.4a. This BFPT is taken as the input in Algorithm 4 to construct the

Algorithm 4: Reliable protection tree designing (RPTD)

```
Input: Breadth-first protection tree (BFPT) for each source node of the physical network.
Output: Reliable protection tree for each source node.
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, ..., |Λ|)
        if (available λ_i) then
            Reserve λ_i as a backup path
        else
            No backup 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 r-x route as a backup path according to wavelength
                    continuity constraint
                else
                    No backup path formed
            else
                Check for available wavelength λ_j, in the link x-u (where j = 1, 2, ..., |Λ|)
                if (available λ_j) then
                    Reserve λ_j (j > i) in the end-to-end route r-x as a protection path
                    according to wavelength continuity constraint
                else
                    No backup path formed
            Mark x as 'visited'
            Enqueue x into the queue, Q
```

reliable protection tree for source node 1 (see Fig. 7.4b). We restrict the sharing of a wavelength in the sub branch of the protection tree. As a result, the end-to-end routes 1–2–8–7, 1–2–3–4–5, and 1–2–3–4–6 do not share a wavelength among themselves; they are assigned with different wavelengths λ_1, λ_2, and λ_3, respectively.

As recovery performance of an optical network is determined by the reliability function, we formulate the average reliability in the network using the reliability function of component *i* over a period of time *t*. The reliability of a component is the probability that the component does not fail in time period *t*. The average reliability in the network, denoted by $N_R(t)$, which is estimated by,

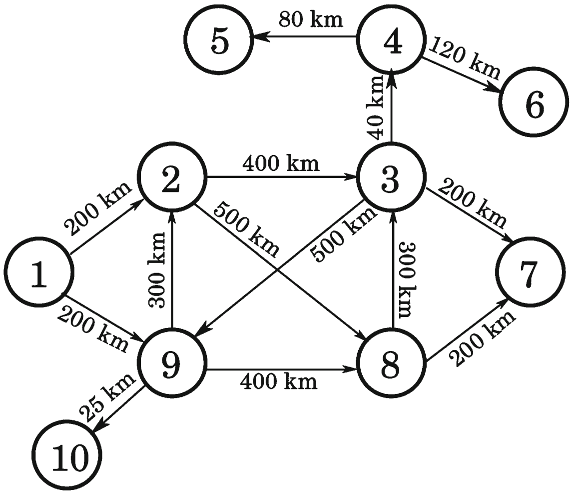

Fig. 7.3 Physical topology of sample network

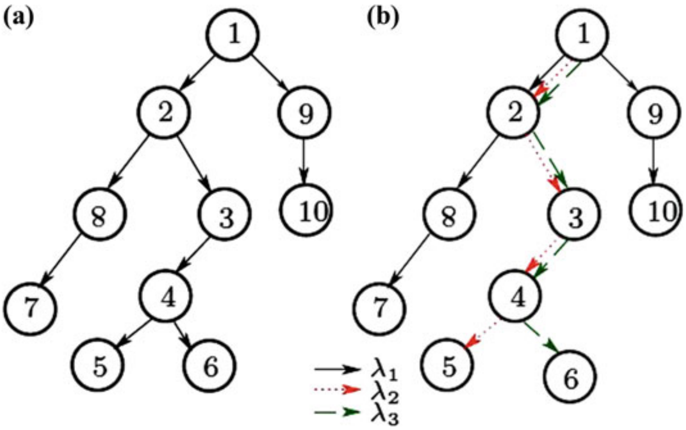

Fig. 7.4 **a** Breadth-first protection tree (BFPT) and **b** reliable protection tree for source node 1

$$N_R(t) = \frac{\sum_{j=1}^{Z} R_j(t)}{Z}, \tag{7.1}$$

where Z represent the number of lightpath requests. $R_j(t)$ is the probability that the lightpath j does not fail over a period of time t as given below.

$$R_j(t) = 1 - \left(1 - \prod_{i \in C_j^{WP}} R_i^{WP}(t)\right)\left(1 - \prod_{i \in C_j^{BP}} R_i^{BP}(t)\right), \tag{7.2}$$

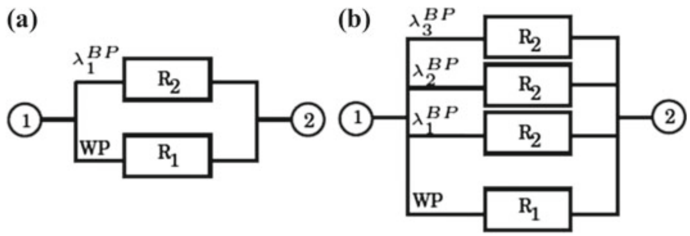

Fig. 7.5 Reliability block diagram using **a** the conventional SP scheme, and **b** the RPTD algorithm from node 1 to node 2

where $R_i^{WP}(t)$ and $R_i^{BP}(t)$ represent the reliabilities of component i for working path and backup path, respectively over a period of time t. C_j^{WP} and C_j^{BP} represent sets of components that the working and backup paths of lightpath j use, respectively. The working and backup paths of lightpath j must be disjoint paths. The reliability of component i does not depend on lightpath j.

We use the reliability model to compare the reliability of the conventional shared protection (SP) scheme and our developed reliable protection trees designing (RPTD) algorithm. In this model, $R_i^{BP}(t)$ (i.e. $0 \leq R_i^{BP}(t) \leq 1$) represents the reliability of component i for the backup path (BP) over a period of time t.

To compare the reliabilities between node 1 to node 2 using the SP scheme and the RPTD algorithm, we consider the reliability block diagram (RBD) as shown in Fig. 7.5. The conventional SP scheme shares one wavelength (see Fig. 7.4a), whereas the RPTD algorithm uses three wavelengths to enhance reliability in sub branches of the tree (see Fig. 7.4b). If any failure occurs in wavelength λ_1 between node 1 to node 2, backup paths 1–2, 1–8, 1–7, 1–3, 1–4, 1–5, and 1–6 are affected in case of the conventional shared protection. However, only backup paths 1–2, 1–8, and 1–7 are affected in the introduced scheme; backup paths 1–3, 1–4, 1–5, and 1–6 are not affected. From this example, we achieve that the reliability in the network using the introduced scheme is higher than that of the traditional one by consuming extra wavelength resources. As the number of wavelengths increases, the end-to-end routes from the root node to leaf nodes having a common link do not share a wavelength among themselves, and hence the possibility of failure backup paths decreases. In other words, we can say that the reliability in the network depends on the number of wavelengths used per fiber link.

The reliability, denoted by $R_j^{SP}(t)$, using the SP scheme of a lightpath j over a period of time t is estimated by,

$$R_j^{SP}(t) = \prod_{H_j} \left[1 - \prod_{i \in C_j^{SP}} (1 - R_i^{BP}(t)) \right], \tag{7.3}$$

where H_j is set of all hops contained by the lightpath j. C_j^{SP} represents set of components that the backup path of lightpath j uses in each hop using SP scheme.

The average reliability in the network, denoted by $N_R^{SP}(t)$, using the SP scheme for all lightpath requests over a period of time t is estimated by,

$$N_R^{SP}(t) = \frac{\sum_{j=1}^{Z} R_j^{SP}(t)}{Z}. \tag{7.4}$$

The reliability, denoted by $R_j^{RPTD}(t)$, of lightpath j using the RPTD algorithm over a period of time t is estimated by,

$$R_j^{RPTD}(t) = \prod_{H_j} \left[1 - \prod_{i \in C_j^{RPTD}} (1 - R_i^{BP}(t)) \right], \tag{7.5}$$

where C_j^{RPTD} represents set of components that the backup path of lightpath j uses in each hop using RPTD algorithm. The average reliability in the network, denoted by $N_R^{RPTD}(t)$ using the RPTD algorithm for all lightpath requests over a period of time t is estimated by,

$$N_R^{RPTD}(t) = \frac{\sum_{j=1}^{Z} R_j^{RPTD}(t)}{Z}. \tag{7.6}$$

As C_j^{RPTD} contains more components than that of C_j^{SP},

$$N_R^{RPTD}(t) \geq N_R^{SP}(t). \tag{7.7}$$

From the above Eqs. (7.3)–(7.7), it is clear that the RPTD algorithm provides higher reliability compared to the conventional SP scheme by using extra resources.

7.5 Performance Analysis

This section presents simulation results of the introduced scheme. The following assumptions are considered for the purpose of simulations. We consider NSFNET [5] and the Indian network [22] as network topologies, which are shown in Fig. 3.1 (p. xxx) and Fig. 3.2 (p. xxx), respectively. The lightpath requests are generated randomly based on a Poisson process and the holding time of lightpath requests follows an exponential distribution. The working path between a source-destination pair is estimated using the shortest path routing and the wavelength assignment of lightpath requests is performed based on first fit policy [5]. The backup path must be link disjoint from the working path. For reliability measurement, we consider the failure rates of each component (say wavelength) of working path, denoted by f_{WP}, and backup path, denoted by, f_{BP}, as 0.01 and 0.005/h, respectively. This failure rates are typically considered for electronic communication systems [23]. The time duration is considered as 24 h.

7.5.1 Reliability Measurement

This subsection presents the performance of the introduced scheme in terms of average reliability, which is estimated using Eq. (7.1). The reliability of each lightpath over a period of time t is estimated by [23],

$$R(t) = e^{-(f_{WP})\cdot t} + \frac{f_{WP}}{f_{WP} - f_{BP}}[e^{-(f_{BP})\cdot t} - e^{-(f_{WP})\cdot t}], \tag{7.8}$$

where f_{WP} and f_{BP} represent the failure rates of each working path and backup path, respectively.

Figure 7.6 shows the average reliability in the network versus failure rate in the working path per hour, obtained by using the introduced reliable fault resilience scheme, the conventional dedicated protection scheme, and the conventional shared protection scheme for the Indian network. In this simulation, the traffic load is considered 10 Erlang and each fiber link contains 20 wavelengths. The average reliability in the network is estimated by using Eqs. (7.1) and (7.8). We observe that the average reliability in the network decreases with increase in failure rate. The conventional dedicated protection scheme provides highest reliability as it reserves dedicated wavelength for each working path. The average reliability using the introduced scheme is higher than that of the conventional shared protection scheme. This is due to the restriction of sharing a wavelength in end-to-end routes from the root node to leaf nodes having a common link using the introduced scheme.

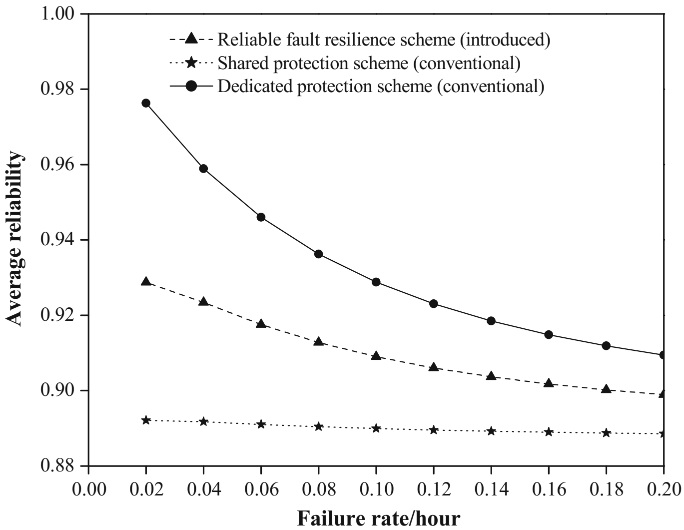

Fig. 7.6 Average reliability versus failure rate/hour, obtained by using different schemes for Indian network

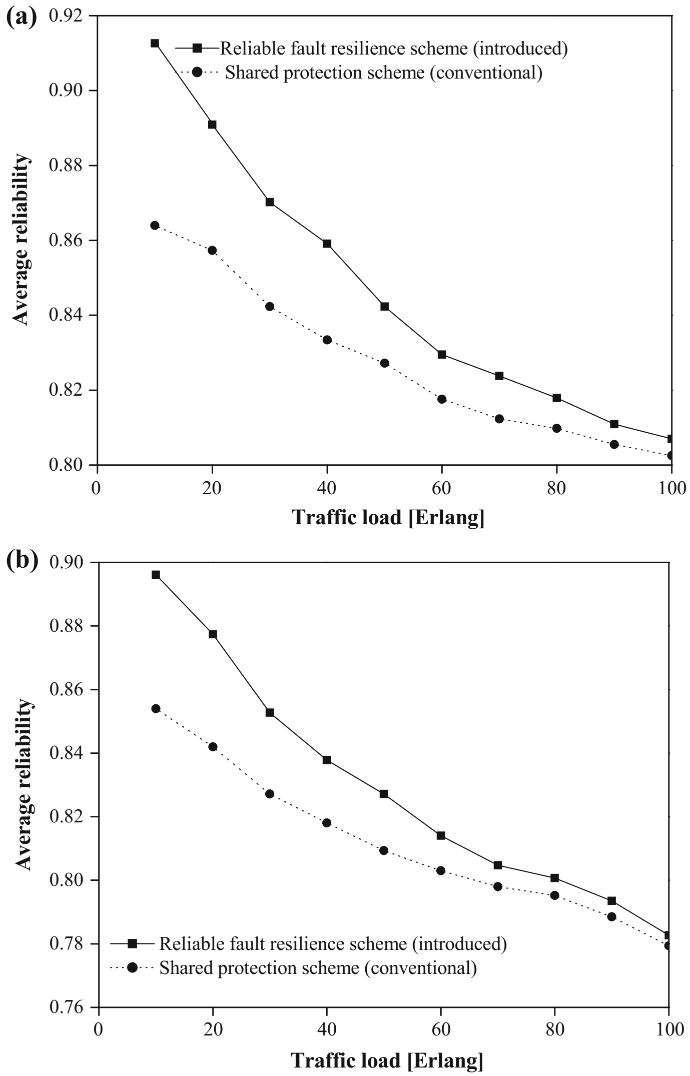

Fig. 7.7 Average reliability versus traffic load, obtained by using different schemes for **a** Indian network and **b** NSFNET

We investigate how the introduced reliable fault resilience scheme works under varied traffic load with a specific number of wavelengths per link. Figures 7.7a and 7.7b show the average reliability in the network versus traffic load using the introduced reliable fault resilience scheme and the conventional shared protection scheme for NSFNET and the Indian network, respectively, when each fiber link contains

10 wavelengths. We observe that the average reliability using the introduced fault resilience scheme is higher than that of the conventional shared protection scheme when the traffic load is low. This is because, under low traffic load, the introduced fault resilience scheme can manage wavelength resources in order to allocate any two different end-to-end routes from the root node to leaf nodes sharing at least one link with different wavelengths. When the traffic load increases, we perceive that the reliability of the introduced fault resilience scheme becomes close to the conventional shared protection scheme. This is because the possibility of restriction of sharing a wavelength in the sub branches of the tree decreases due to the limited number of wavelength resources as traffic load becomes high. Furthermore, we perceive that the average reliability using the introduced scheme in the Indian network is higher compared to NSFNET due to the effect of average node degree in the network. The average node degree in the Indian network is 3.43, which is greater than that of the average node degree (3) in NSFNET.

7.5.2 Blocking Probability

This subsection evaluates the performance of the introduced scheme and the conventional shared protection scheme in terms of blocking probability, which is defined as a ratio of the number of blocked lightpath requests to the number of lightpath requests in the network.

Figures 7.8a and 7.8b show the blocking probability versus traffic load [Erlang], obtained by different schemes for the Indian network and NSFNET, respectively. We perceive that the blocking probability increases with increase in traffic load. The blocking probability using the conventional dedicated scheme is highest as it reserves a wavelength channel for each working path. Furthermore, we observe that the reliable fault resilience scheme provides higher blocking probability compared to the conventional shared protection scheme. This is because, the reliable fault resilience scheme adopts reliable protection tree designing algorithm to construct reliable shared protection trees in order to provide higher reliability to the established lightpaths, which uses extra resources compared to the conventional shared protection scheme.

From the above discussion, we summarize that the conventional dedicated protection scheme provides higher reliability compared to other schemes. The conventional shared protection scheme outperforms other schemes in terms of blocking probability. The introduced reliable fault resilience scheme tradeoffs between network reliability and blocking probability.

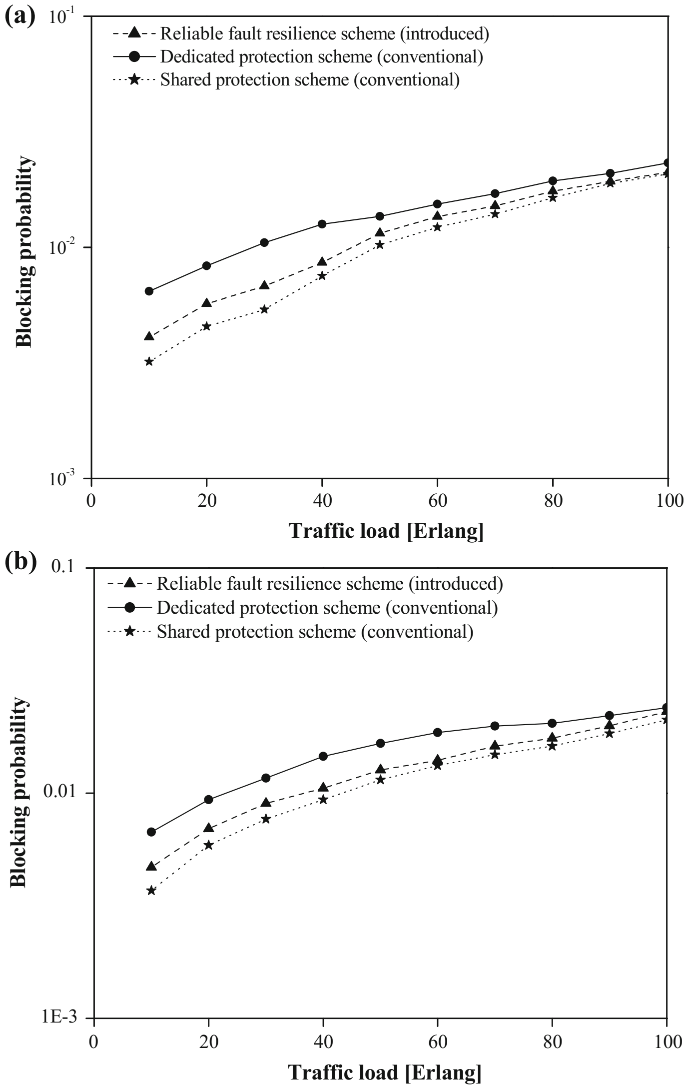

Fig. 7.8 Blocking probability versus traffic load, obtained by using different schemes for **a** Indian network and **b** NSFNET

7.6 Conclusion

This chapter presented a reliable fault resilience scheme for optical networks in order to improve the network reliability. In the introduced scheme, the established lightpaths are protected using the reliable shared protection tree in order to improve the reliability in the network. The simulation results indicated that the introduced scheme improves the average reliability in the network compared to the conventional shared protection scheme. The introduced reliable fault resilience scheme provides a new class of service, which tradeoffs between network reliability and blocking probability.

Till now we investigated the RWA problem for suppressing the call blocking, improving the quality-of-service (QoS) in terms of Q-factor and reliability in WDM-based optical networks. Recently WDM-based optical networks faces a number of limitations, and these limitations can be overcome by elastic optical networks. We will address this issue in the next chapter.

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Chapter 8
Limitations of Conventional WDM Optical Networks and Elastic Optical Networks for Possible Solutions

8.1 Introduction

Internet traffic volume is outpacing the technology advancements in networking. Cisco's Visual Networking Index [1] expects that the worldwide Internet protocol (IP) traffic hit 20.2 Exabytes per month in 2020, and 242 Exabytes per year. Therefore, optical networks will be required to support Tb/s class transmission in the near future [2, 3]. Unfortunately, conventional optical transmission technology has inadequate scaling performance to meet the growing traffic demands as it suffers from the electrical bandwidth bottleneck limitation, and the physical impairments become more serious as the transmission speed increases [4]. Moreover, the traffic behavior is changing rapidly and the increasing mobility of traffic sources makes grooming [5–9] more complex. Therefore, researchers are now focusing on new technologies for high-speed optical networks.

To meet the needs of the future Internet, optical transmission and networking technologies are moving toward to the goals of greater efficiency, flexibility, and scalability. Recently, elastic optical networks [10–22] have been shown to be a promising candidate for future high-speed optical communication. An elastic optical network has the potential to allocate spectrum to lightpaths according to the bandwidth requirements of clients. The spectrum is divided into narrow slots and optical connections are allocated a different numbers of slots. As the result, network utilization efficiency is greatly improved compared to DWDM-based optical networks. In elastic optical networks, a certain number of transmission parameters, such as — optical data rate, modulation format, and wavelength-spacing between channels, which are fixed in currently deployed networks, will be made tunable. Given that future demands indicate that high-speed optical connections are needed to optimize data transport, elastic optical networks are a suitable replacement for WDM-based optical networks.

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The rest of the chapter is organized as follows. Section 8.2 provides the basic concept of the elastic optical network. Section 8.3 presents the architecture of the elastic optical network. The different node architectures are explained in Sect. 8.4. Finally, Sect. 8.5 concludes this chapter.

8.2 Concept of Elastic Optical Networks

The traditional WDM-based optical network divides the spectrum into separate channels. The spacing between adjoining channels is either 50 or 100 GHz, which is specified by international telecommunication union (ITU)-T standards as shown in Fig. 8.1. The frequency spacing between two adjacent channels is relatively large. If the channels carry only low bandwidth, and no traffic can be transmitted in the large unused frequency gap, a large portion of the spectrum will be wasted, which is reflected in Fig. 8.2.

To overcome the limitations of traditional optical networks, M. Jinno et al. [11] presented a spectrum efficient elastic optical network based on OFDM technology [15, 23]. Optical OFDM allocates the data to several low data rate subcarrier channels. As the spectrum of adjacent subcarrier channels are orthogonally modulated, they can overlap each other as shown in Fig. 8.3, which increases transmission spectral efficiency. Furthermore, optical OFDM can provide fine-granularity capacity to connections by the elastic allocation of low rate subcarriers. A bandwidth-variable OFDM transponder generates an optical signal using just enough spectral resources, in terms of subcarriers with appropriate modulation level, to satisfy the clients requirements. OFDM signals are usually generated in the radio-frequency domain,

Fig. 8.1 ITU-T grid

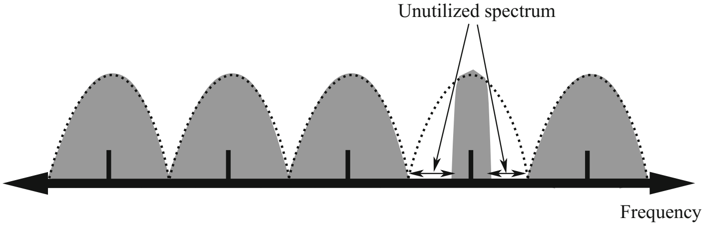


Fig. 8.2 Spectrum allocation in WDM based optical networks

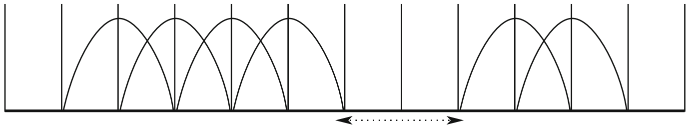


Fig. 8.3 Overlapping subcarriers caused by OFDM technology

so many transmission properties can be freely set, i.e., different subcarriers can be assigned different numbers of modulated bits per symbol. To establish a connection, each bandwidth variable cross-connect on the route allocates a cross-connection with sufficient spectrum in order to create an appropriately sized end-to-end optical path. This end-to-end path is expanded and contracted according to the traffic volume and user requests, as necessary. The main characteristics of an elastic optical network are bandwidth segmentation, bandwidth aggregation, efficient accommodation of multiple data rates, elastic variation of allocated resources, reach-adaptable line rate, etc. These are discussed in more detail below.

- Bandwidth segmentation: Traditional optical networks require full allocation of wavelength capacity to an optical path between an end-node pair. However, elastic optical networks provide a spectrum efficient bandwidth segmentation (sometimes called sub wavelength) mechanism that provides fractional bandwidth connectivity service. If only partial bandwidth is required, elastic optical network can allocate just enough optical bandwidth to accommodate the client traffic, as shown in Fig. 8.4, where a 40 Gb/s optical bandwidth is segmented into three sub wavelengths, such as — 5, 15 and 20 Gb/s. At the same time, every node on the route of the optical path allocates a cross-connection with the appropriate spectrum bandwidth to create an appropriate-sized end-to-end optical path. The efficient

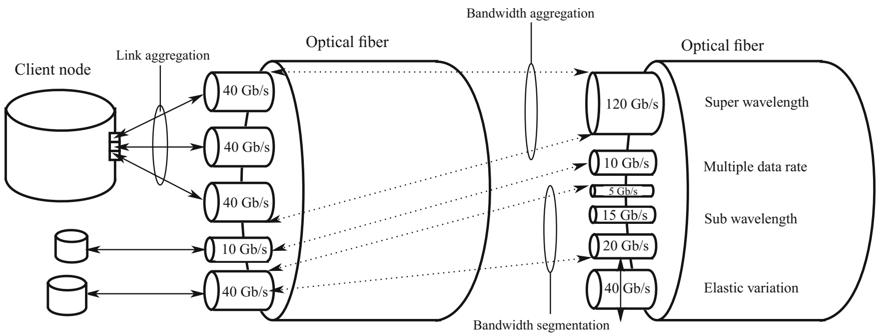


Fig. 8.4 Unique characteristics, namely — bandwidth segmentation, bandwidth aggregation, accommodation of multiple data rates, and elastic variation of allocated resources, of elastic optical networks

use of network resources will allow the cost-effective provisioning of fractional bandwidth service.

- Bandwidth aggregation: Link aggregation is a packet networking technology standardized in IEEE 802.3. It combines multiple physical ports/links in a switch/router into a single logical port/link to enable incremental growth of link speed as the traffic demand increases beyond the limits of any one single port/link. Similarly, the elastic optical network enables the bandwidth aggregation feature and so can create a super-wavelength optical path contiguously combined in the optical domain, thus ensuring high utilization of spectral resources. This unique feature is depicted in Fig. 8.4, where three 40 Gb/s optical bandwidths are multiplexed with optical OFDM, to provide a super-channel of 120 Gb/s.
- Efficient accommodation of multiple data rates: As shown in Fig. 8.4, the elastic optical network has the ability to provide the spectrally-efficient direct accommodation of mixed data bit rates in the optical domain due to its flexible spectrum assignment. Traditional optical networks with fixed grid leads to wastage of the optical bandwidth due to the excessive frequency spacing for low bit rate signals.
- Reach-adaptable line rate: The elastic optical network has the ability to support reach-adaptable line rate, as well as dynamic bandwidth expansion and contraction, by altering the number of subcarriers and modulation formats.
- Energy saving: It supports energy-efficient operations in order to save power consumption by turning off some of the OFDM subcarriers while traffic is slack.
- Network virtualization: It allows optical network visualization with virtual links supported by OFDM subcarriers.

8.3 Elastic Network Architecture

To fulfill our ever-increasing bandwidth demands, the elastic optical network is indispensable. This is due to its many desirable properties including flexible data rate and spectrum allocation, low signal attenuation, low signal distortion, low power requirement, low material usage, small space requirement, and low cost. This section discusses the architecture of the elastic optical network. Figure 8.5 shows the typical architecture of the elastic optical network, which mainly consists of BVTs and BV-WXCs. These basic components and their working principle are explained in the following subsections.

8.3.1 Bandwidth-Variable Transponder

BVTs [15] are used to tune the bandwidth by adjusting the transmission bit rate or modulation format. BVTs support high-speed transmission using spectrally efficient modulation formats, e.g., 16-quadrature amplitude modulation (QAM), with

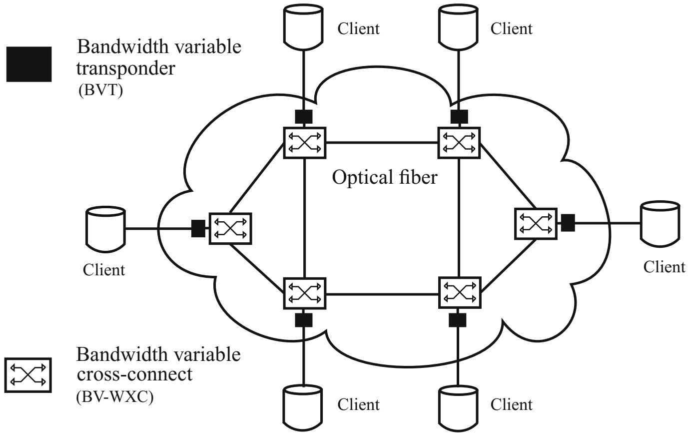


Fig. 8.5 Architecture of elastic optical network

64-QAM used for shorter distance lightpaths. Longer distance lightpaths are supported by using more robust but less efficient modulation formats, e.g., quadrature phase-shift keying (QPSK) or binary phase-shift keying (BPSK). Therefore, BVTs are able to trade spectral efficiency off against transmission reach.

However, when a high-speed BVT is operated at lower than its maximum rate due to required reach or impairments in the optical path, part of the BVT capacity is wasted. In order to address this issue, an SBVT [24–28] has been presented that offers improved flexibility; it is seen as a promising transponder technology. An SBVT has the capability to allocate its capacity into one or several optical flows that are transmitted to one or several destinations. Therefore, when an SBVT is used to generate a low bit rate channel, its idle capacity can be exploited for transmitting other independent data flows. An SBVT generates multiple optical flows that can be flexibly associated with the traffic coming from the upper layers according to traffic requirements. Therefore, optical flows can be aggregated or can be sliced based on the traffic needs. Figure 8.6 distinguishes BVT and SBVT functionalities.

The SBVT architecture [24, 25] was introduced in order to support sliceability, multiple bit rates, multiple modulation formats, and adaptive code rates. Figure 8.7 shows the architecture of an SBVT; it mainly consists of a source of N equally spaced subcarriers, a module for electronic processing, an electronic switch, a set of N photonic integrated circuits (PICs), and an optical multiplexer. In this architecture, the N subcarriers are generated by a single multi wavelength source. However, such a source may be replaced by N lasers, one per subcarrier. Each client is processed in the electronic domain (e.g., for filtering) and then is routed by the switching matrix to a specific PIC. The generated carriers are equally spaced according to the spectral requirements and transmission technique adopted. Generated subcarriers are selected at the multi wavelength source, and they are routed the appropriate PICs. Each PIC

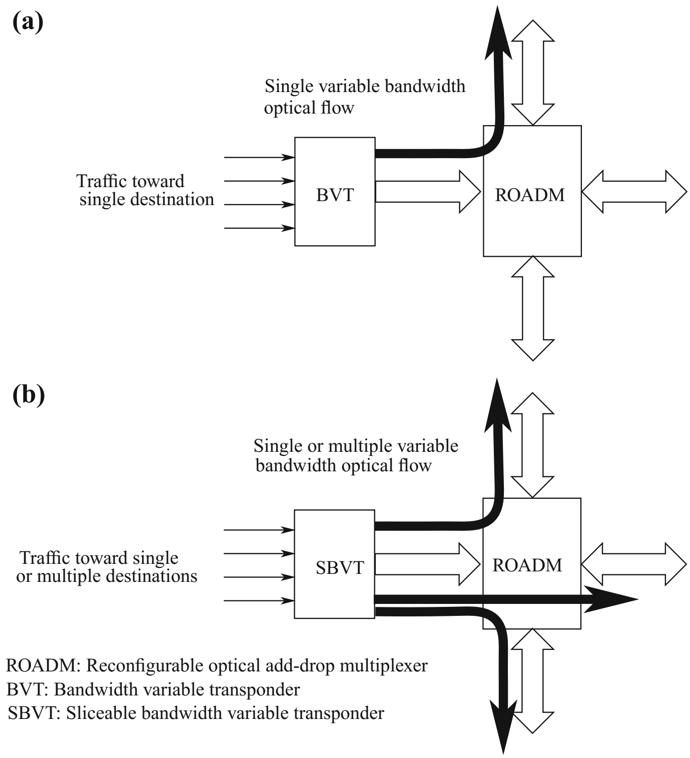
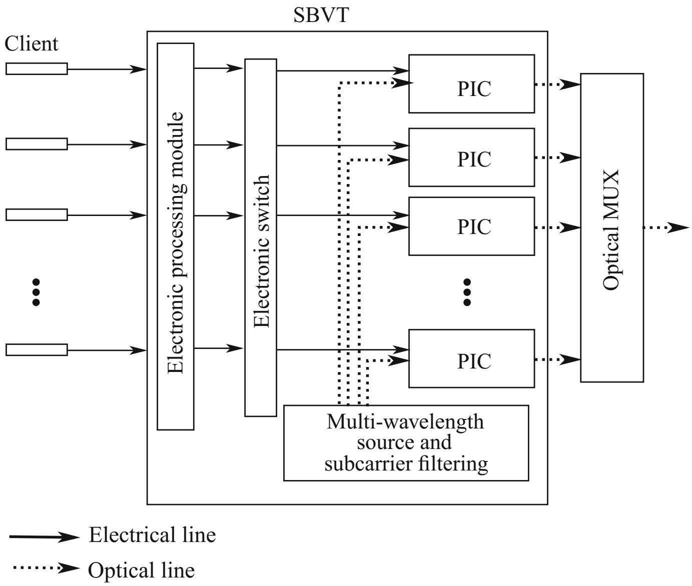


Fig. 8.6 Functionalities of **a** BVT, and **b** SBVT

is utilized as a single-carrier transponder that generates different modulated signals, such as 16-QAM and QPSK, in order to support multiple modulation formats. Finally, subcarriers are aggregated by the optical multiplexer in order to form a super channel. Sometime, subcarriers may be sliced and directed to specific output ports according to the traffic needs. A detailed description of PIC generation of different modulated signals is given in [25].

8.3.2 Bandwidth-Variable Cross-Connect

The BV-WXC [11] is used to allocate an appropriate-sized cross-connection with the corresponding spectrum bandwidth to support an elastic optical lightpath. Therefore, a BV-WXC needs to configure its switching window in a flexible manner according to the spectral width of the incoming optical signal.

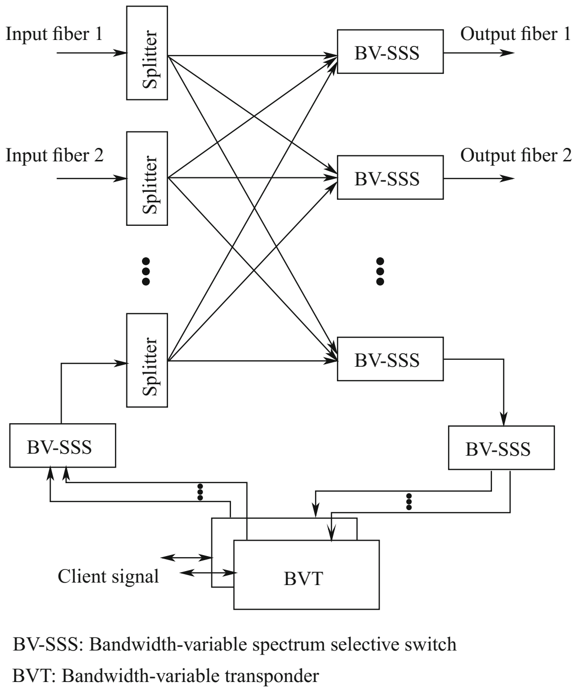


SBVT: Sliceable bandwidth variable transponder
PIC: Photonic integrated circuit
MUX: Multiplexer

Fig. 8.7 Architecture of SBVT

Figure 8.8 shows an implementation example of a BV-WXC, where bandwidth-variable spectrum selective switches (BV-SSSs) in the broadcast-and-select configuration are used to provide add-drop functionality for local signals as well as groomed signal, and routing functionality for transit signals. Typically, a BV-SSS performs wavelength demultiplexing/multiplexing and optical switching functions using integrated spatial optics. The light from an input fiber is divided into its constituent spectral components using a dispersive element. The spatially-separated constituent spectra are focused on a one-dimensional mirror array and redirected to the desired output fiber. Liquid crystal on Silicon (LCoS) or Micro-Electro Mechanical System (MEMS)-based BV-SSSs can be employed as switching elements to realize an optical cross-connect with flexible bandwidth and center frequency. As the LCoS is deployed according to phased array beam steering, which utilizes a large number of pixels, LCoS-based BV-SSSs can easily provide variable optical bandwidth functionality. A detailed description of a BV-WSS employing LCoS technology can be found in [23, 29]. Similarly, details of an MEMS-based BV-SSS can be found in [23, 30].

Fig. 8.8 Architecture of BV-WXC



8.4 Node Architectures

This section discusses various node architectures [31, 32], which are the building blocks of spectrum efficient elastic optical networks.

8.4.1 Broadcast-and-Select

The broadcast-and-select architecture has been used to determine the elastic optical node architecture that uses spectrum selective switches [32]. Figure 8.9 shows the node architecture of broadcast-and-select, which is implemented using splitters at the input ports. Splitters are used to generate copies of the incoming signals that are subsequently filtered by spectrum selective switches in order to select the required signals at the receiver side. The add/drop network may implement colorless, directionless, and contention-less elastic add/drop functionality, thus allowing the addition of one or more wavelength channels to an existing multi-wavelength signal automatically. It can also drop (remove) one or more channels from the passing signals to another network path dynamically. The main drawbacks of the broadcast-and-select node architecture are as follows - (i) it requires synchronization and rapid tuning,

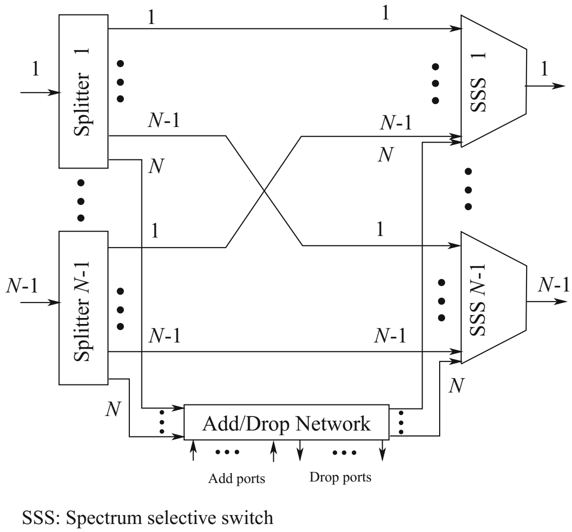


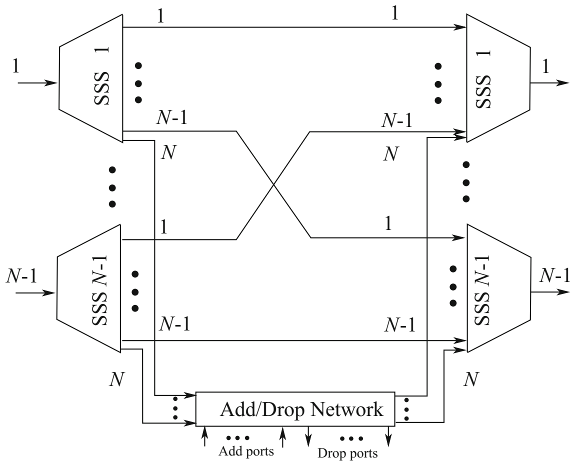
Fig. 8.9 Node architecture of broadcast-and-select

(ii) it cannot support wavelength reuse and hence a large number of wavelength channels is required, (iii) the signal power is split among various nodes, so this type of node cannot be used for long distance communication. The broadcast and select architecture is mostly being used in high-speed local area networks and metropolitan area networks. It must noted that the broadcast-and-select architecture struggles to support additional functionality to cope with dynamic requirements, e.g., spectrum defragmentation [33–35].

8.4.2 Spectrum Routing

The spectrum routing node architecture is being designed to overcome the problems with the broadcast-and-select node architecture. It is basically implemented with arrayed waveband gratings [23] and optical switches as shown in Fig. 8.10. In spectrum routing, both switching and filtering functionalities are controlled by the spectrum selective switches. The basic advantage of this architecture, compared to the broadcast-and-select architecture, is that the through loss is not dependent on the number of degrees. However, it requires additional spectrum selective switches at the input fibers, which makes it more expensive to realize. Furthermore, the additional functionality needed to cope with dynamic requirements, e.g., spectrum defragmentation [33–35], is still difficult to implement in this architecture.

Fig. 8.10 Node architecture of spectrum routing



8.4.3 Switch and Select with Dynamic Functionality

We have already observed that the broadcast-and-select architecture and spectrum routing architecture are unable to support dynamic requirements, such as, spectrum defragmentation, time multiplexing, regeneration, etc. To overcome these limitations, the switch and select architecture with dynamic functionality has been introduced. In this architecture, an optical switch is used to direct copies of the input to a specific spectrum selective switch or to a module (f) that provides additional functionalities, such as — defragmentation, time multiplexing, and regeneration. The outputs of the modules connect to spectrum selective switches, where the required signals are filtered for delivery to the corresponding output fiber. Figure 8.11 shows the node architecture of the elastic optical network with the dynamic functionalities that support dynamic requirements, namely — spectrum defragmentation, time multiplexing, and regeneration. These dynamic functionalities come at the price of additional large port count optical switches and larger spectrum selective switch port counts. The number of ports is dedicated to provide a specific functionality, and hence the number of modules may be calculated from the expected demand.

8.4.4 Architecture on Demand

The architecture on demand (AoD) [36] consists of an optical backplane that is implemented with a large port-count optical switch connected to several processing modules, namely — spectrum selective switch, fast switch, erbium-doped fiber amplifier (EDFA), spectrum defragmenter, splitter, etc. The inputs and outputs of

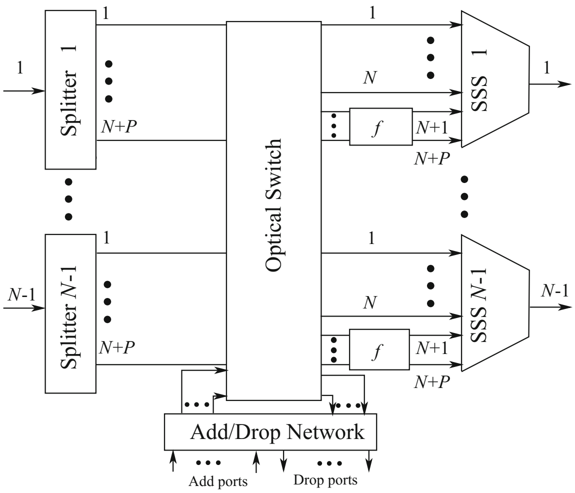


Fig. 8.11 Node architecture of switch and select with dynamic functionality

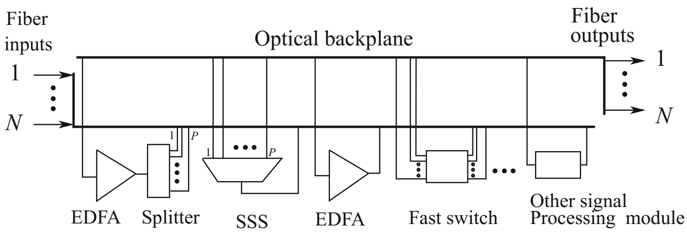


Fig. 8.12 Node architecture on demand with *N* input/outputs, and signal processing modules

the node are connected via the optical backplane as shown in Fig. 8.12. The different arrangements of inputs, modules, and outputs are realized by setting appropriate cross connections in the optical backplane. Therefore, it provides greater flexibility than the architectures explained above. This is mainly due to the non-mandatory nature of the components (such as — spectrum selective switch, power splitters and other functional modules) unlike static architectures, but they can be interconnected together in an arbitrary manner. The number of spectrum selective switches and other processing devices is not fixed but can be determined based on the specific demand for that functionality. Thus, savings in the number of devices can balance the additional cost of the optical backplane, and hence this type of architecture provides a cost-efficient solution. Furthermore, AOD provides considerable gains in terms of scalability and resiliency compared to conventional static architectures.

Table 8.1 Comparison of different node architectures for the elastic optical network

	Broadcast-and-select	Spectrum routing	Switch and select with dynamic functionality	Architecture-on-demand
Power loss [in dB] [32]	$3\lceil\log_2(N)\rceil + L_{SSS}$	$2L_{SSS}$	$3\lceil\log_2(N+P)\rceil + L_{SSS} + L_{Switch} + L_M$	Switch and select architecture + $(m+1)L_{\text{Switch}}$ for path with m modules
Switch/backplane port count [32]	Not required	Not required	$N(N+P)$	$2(N-1) + N(N+P)$
Routing flexibility	No	No	Medium	High
SSS port count	N	N	$N+P$	P
Defragmentation	No	No	Yes	Yes
Time multiplexing	No	No	Yes	Yes
Regeneration	No	No	Yes	Yes

SSS: Spectrum selective switch, L_{SSS}: SSS loss, L_{Switch}: Switch/backplane loss, L_M: Module loss

8.4.5 Comparing Node Architectures

Table 8.1 summarizes the above discussed node architectures in terms of total power loss, port count of switch/backplane, routing flexibility, port count of spectrum selective switches, defragmentation capability, time multiplexing, and regeneration capability. The calculation of total power loss [32] is determined by the type of node architecture implemented. In case of AOD, total power loss depends on the architecture implemented and the number of cross connections used in the optical backplane. The total power loss in the switch and select with dynamic functionality architecture depends on the spectrum selective switches, backplane, and modules used. However, the total power losses of the broadcast-and-select architecture and spectrum routing architecture mainly depend on the spectrum selective switches.

Port count of switch/backplane [32] varies the networking cost. The switch and select node and AOD node architectures need optical switches. However, the number of SSSs and other processing devices may be tailored to suit the specific demand. Therefore, as savings in the number of devices can offset the additional cost of the optical backplane, it provides an overall cost-effective solution. The number of SSS ports required by an AoD node is not strictly related to the node degree. This is because several small-port-count SSSs may be connected together in order to increase the number of available ports.

Routing flexibility is the capability of the system to carry signals from source to destination along different routes. This type of flexibility is required when strengthening system resilience to failures along working paths; signals may be directed to their backup paths. Time multiplexing is used to transmit and receive independent signals over a common signal path by synchronized switches at each end of the transmission line. As a result, each signal appears on the line only a fraction of the time in an alternating pattern. On the other hand, all-optical 3R (Re-amplification, Re-shaping, and Re-timing) signal regeneration is needed to avoid the accumulation of noise, crosstalk and non-linear distortion, and to ensure good signal quality for transmission over any path in an optical network. Spectral defragmentation is a technique to reconfigure the network so that the spectral fragments can be consolidated into contiguous blocks.

8.5 Conclusion

This chapter presented the limitations of WDM optical networks, and introduced elastic optical networks for future high-speed communications. The basic concept of the elastic optical network and its unique properties are explained and then turned to its architecture and operation principle. The architecture of SBVT and its advantages in the future optical networking were detailed. Immediately after discussing network architecture, the discussion focused on the different node architectures, namelybroadcast and select, spectrum routing, switch and select with dynamic functionality, and architecture on demand, along with their functionalities. Finally, this chapter compared the different node architectures and their performances in terms of scalability and flexibility.

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